AGRICULTURAL MECHANISATION SYSTEMS ANALYSIS - TRACTOR POWER SELECTION FOR TILLAGE OPERATIONS

BY

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ABSTRACT OF THESIS (Regulation 6.9)

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Title of Thesis AGRICULTURAL MECHANISATION SYSTEMS ANALYSIS - TRACTOR POWER SELECTION FOR TILLAGE OPERATIONS

Primary tillage largely dictates the power requirement on an arable farm. As power and achinery costs continue to rise, it is important to provide a sound management base for the ptimum selection of tractor size. A tractor power selection programme has been developed by xamining a single operation for a single crop, namely, ploughing for cereals.

The tractor power selection programme comprises seven essential sections each of which an be used separately and independently depending on the type of the output required. The even major steps are the prediction of soil moisture, soil workability, soil strength, ractor performance, plough draught and system cost and the selection of a limited number of uitable tractor plough combinations.

For the prediction of daily fluctuations of soil moisture content, the amount of water ained by the soil is balanced against the amount of water lost. Water added to the soil in he form of precipitation and irrigation is lost by means of evapotranspiration, drainage nd surface run-off. Potential evaporation is calculated by means of an empirical equation sing mean monthly air temperature and converted to actual evaporation from the soil and ranspiration from vegetation where present. Factors are incorporated to correct for the ryness of the soil, the duration and intensity of precipitation and the stage of the crop hich is covering the soil. Daily values of drainage flux was calculated from the hydraulic onductivities and moisture content of the soil at saturation and field capacity and soil oisture content prior to commencement of drying. Existing empirical procedures were utilised o calculate run-off.

By analysing the predicted soil moisture contents, each calendar day can be assigned as uitable for farm work (a work day) or unsuitable for a given operation (non-work day). As oil workability varies from soil to soil, machine to machine and farm manager to farm manager, he adoption of a unique soil moisture value to differentiate between soil workability and on-workability is unrealistic. A procedure has therefore been adopted to enable the number f work days to be calculated at different levels of soil moisture content or workability riteria. The data is analysed for a number of years (up to 20) and then the cumulated number f years on which a given day was a work day or a non-work day with a given workability riterion was determined for different probability levels. This data is of direct relevance ot only to machinery planning but also to irrigation planning and for timeliness penalty valuation.

Soil strength in terms of the cone penetrometer resistance or cone index of the soil at a iven soil workability criterion level is predicted by an empirical equation containing soil ulk density. The cone index influences the pull produced by the tractor for a given set of yre and deflection data and the tractor power required. It also affects the draught requirements of the plough of given dimensions, tail angle, number of bodies and depth of cut.

The cost of owning a machinery system is calculated in the form of the present annual cost, aking into account the effect of inflation and interest rate by using discounted cash flows. he purchase prices of tractors and implements were related to the average price per unit of ower and per unit width of plough, respectively. Crop loss or timeliness penalties through elayed operations are also determined.

Finally, the various different ploughing systems with different sizes of tractors and loughs and at different operations speeds are examined and a small number of suitable systems re presented in a form which enables the farmer or farm manager to take into account other nique management parameters of his particular farm business.

DECLARATION

This thesis is a report of research conducted by the undersigned and is of an original nature. None of the work reported has been published or presented for any other degree or professional qualification unless otherwise mentioned.

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KEY TO SYMBOLS

Notation	Title	Units
a	depth of cut	m
$a_1, a_2, \ldots a_i$	coefficients	
A	exponent	
APULL	actual tractor pull produced at drawbar	kN
AREA	area of the field	ha
ASM	antecedent soil moisture index	mm
ASN	actual sunshine hours	h
AWC	available water content of soil	mm
b	tyre width	m
$b_1, b_2, \ldots b_i$	coefficients	
B	empirical constant	kN
BALL	tyre ballasting	
BD	soil bulk density	g/cm^3
$c_1, c_2, \ldots c_i$	coefficients	
CA	amount of water condensing into the soil	mm
CAP	initial capital	£
CC	crop stage correction factor	
CI	cone index	kPa,
CRR_F	coefficient of rolling resistance, front wheel	
CT	coefficient of traction	
CT_{max}	coefficient of traction at maximum efficiency	
CY_1, CY_2, CY_3	coefficients of yield function	
d	tyre diameter	m
D	plough draught	kN
DAY	day number for which soil moisture content is being calculated	
DC	soil dryness correction factor	
Dp and Dm	predicted and measured plough draught	kN
DRAIN	soil water flux (drainage)	mm/day
$DRAIN_1$ and $DRAIN_O$	amount of drainage water entering and leaving the soil segment	mm/day
$DRAIN_{MR}$ and $DRAIN_{PR}$	predicted and measured drainage	mm/day

Key to Symbols - cont'd

DS	constant	
e	Naperian logarithm constant	
ET	evapotranspiration or actual evaporation	mm
f	function of	
FC	soil water content at field capacity	mm
FL	factor	
gi	inflation rate	%
g	gravitational acceleration	m/s^2
h	tyre section height	m^2
hi	soil depth	mm
h'	control factor	
HOURS	number of hours required to complete ploughing	h
i	constant	
I	$\sum_1^{12} i$	
INT'	amount of water intercepted by trees and vegetation	mm
k	constant	
$k_{1}, _{3}, \ldots k_i$	coefficients	
K_2	sand number	
K	unsaturated hydraulic conductivity	mm/day
K_{fc} and K_{sat}	hydraulic conductivity at field capacity and saturation	mm/day
LC	length of day correction factor	
LCOST	labour cost for ploughing	£
LM	time span	
LYCT	total yearly salary of the operator	£
m'	control factor	
M	soil moisture content	mm or % w/w
ML	ratios of available soil moisture to available soil moisture capacity	
M_{sat} and M_{fc}	soil moisture content at saturation and field capacity	mm
n	subscript referring to number of drive wheels and day number	

Key to Symbols - cont'd

n'	control factor	
N	machine age	Year
NB	number of plough bodies	
P	potential function	
P1	the amount of rainfall prior to commencement of run-off	mm
PAC	present annual cost of machine	£
PAFC	work rate of plough	ha/h
PDL	potential daylight hours	h
PE	potential evaporation	mm/day
PHOURS	number of potential working hours per day	h
Pi	tyre pressure	kPa
POWER	tractor rated power	kW
PPP	plough purchase price	£
PR	precipitation	mm/day
PRICE	price of the produced crop	£
PSC	percent soil surface cover	%
PULL	tractor pull	kN
PWP	plant permanent wilting point	mm
Q	torque	Nm
QR	constant	
r	interest rate	%
R	rainfall	mm
RC	rainy day correction factor	
REP	repair cost	£
RM	level of ML until DC = 1	mm
RR	rolling resistance	kN
RUN	surface run off	mm/day
RUN_1 and RUN_0	amount of surface run off entering and leaving the soil	mm/day
s	slip	%
SC	soil surface cover correction factor	
SM	soil moisture notation	
SN	current resale value of an N year old machine	£
$t_{1,2,3 \ldots i}$	time	

Key to Symbols - cont'd

T 1	mean monthly air temperature	^{o}C
TC	timeliness cost	£
TE	tractive efficiency	%
TFCOST	fuel cost	£
THOUR	total hours of tractor utilisation	h
TIME	sowing date	
TN	soil moisture tension	bar
t_o	maximum yield time	
t_{os}	optimum sowing time	
TPP	tractor purchase price	£
TPULL	theoretical pull of the tractor	kN
TR	travel reduction	m
u	tractor fuel energy content	kWh/1
UFCOST	cost of unit fuel	£/1
V	actual ploughing speed	m/s
V_o	no slip speed	m/s
VAP_1 and VAP_O	amount of water vapour entering and leaving the soil segment	mm/day
w	width of plough body	m
W	tyre load	kN
W_f	tyre load on front wheel	kN
W_o	value of load which produces no measurable deflection at zero inflation pressure	kN
WmN	wheel mobility number	
	independent variable	
	horizontal distance	m
y	dependent variable	
Yave	average yield obtained when crop was sown over a period starting at t_1 and finishing at t_2	t/ha
YIELD	crop yield at time 'TIME'	t/ha
Ymax	yield obtained when crop was sown at time t_o	t/ha
Z	specific plough draught	kN
Z_o	quasi static component of specific draught	
α	exponent	

Key to Symbols - cont'd

δ	tyre deflection	m
Δ	rate of variation of variables	
Θ	volumetric soil water content	cm^3/cm^3
Θ'	plough tail angle at mouldboard end	rad.
ν	soil specific weight	kN/m^3
ε	factor	
σ	soil stress factor	
Φ	soil water pressure head	mm
ω	angular velocity	rev/s

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2. INTRODUCTION

Labour and machinery costs are a major item of expenditure on the arable farm. Unlike other "fixed" costs such as those for seeds, fertilizers and feedingstuffs, there is a greater opportunity for savings through careful selection of the individual components of the mechanisation system by varying the number and size of tractors in relation to the labour force and by correctly matching equipment. It is not only because rising "fixed" costs that more careful machinery selection is important. The need for fuel economy measures and amelioration of the effect of short term fuel shortage have gained greater prominence in farm management strategy. Greater prominence to one factor in a complex series of interactions almost inevitable leads to the neglect of another. Machinery replacement policy is often based on stop gap solutions as a result of minor irrations through recent machine breakdowns or spells of bad weather without reference to the effect of such delays on crop costs and enterprise profitability. The purpose of this project is to provide an effective management procedure for tractor power selection on an arable farm, taking into account all the pertinent variables.

Owing to the complexity of the problem, the initial approach was to consider the operations demanding the highest use of draught power, namely, primary tillage, but to develop a selection procedure in such a way that other operations could be included at a later stage. The objective was to select tractor size from a knowledge of pedological, agronomic, meteorological, engineering and economic constraints imposed on an individual farm. This involved relating tractive performance and machine draught requirements to soil and weather variables, evaluating rate of work and crop timeliness penalties and balancing the various costs involved to select a few feasible solutions.

As the study encompassed such a wide range of disciplines, the literature review is necessarily comprehensive and in many aspects it was possible to incorporate available data in the selection model. Two important links in the proposed procedure required further detailed investigation, namely, the prediction of soil strength from soil moisture content and the evaluation of the time available for working on the soil.

For the first link, cone index was adopted as a single parameter measuring soil strength because it not only was incorporated in predictive equations for traction and draught but also was found to be a function of soil moisture content. In this way tractor and implement size and operating costs could be related directly to farm soil type and location. For the second link, a method was developed to evaluate the days suitable for working on the soil which simulates farming practice, that is, the soil workability criterion could be varied with the vagaries of the weather, the time in hand and the rate of work of the tackle available. This was a major advance on current procedures which base work day probabilities on a fixed workability criterion but which has little practical application.

As the feasibility of these two links could be demonstrated only through the investigation until a complete selection programme was evolved for at least one enterprise. Winter cereals were chosen as the most suitable crop for the purpose because sowing dates are directly dictated by the completion date of the tillage operations.

It is clearly shown in the thesis that the techniques which have been adopted are compatible and result in a limited number of realistic alternatives with different requirements for fuel, labour and machinery.

Further work is now required on a sensitivity analysis and on an extension of the programme to spring sown crops by an adaptation of the computational procedures which have been evolved.

3. LITERATURE REVIEW

3.1 Mechanisation Systems Analysis

Coales, J.F. (1969) proposed that a farm satisfied the definition of a system which was presented in the May 1967 issue of the Newsletter of the I.E.E.E. Group on Systems Science and Cybernetics: "A system is a collection of interacting diverse functional units, such as biological, human, machine, information and natural elements, integrated with an environment to achieve a common objective by manipulation and control of materials information, energy and life." The definition emphasises the need for measuring and evaluation of essential variables incorporated in the mathematical models of the processes which jointly govern the effectiveness of the systems approach.

Hunt (1968) was more specific and argued that the collection of machinery on a farm is a system because it has the two characteristics of a system, i.e. inter-dependence and interaction of its elements. He proposed, therefore, a systems approach to select an appropriate machinery complement (system) for a farm.

3.2 Need for Efficient Machinery Selection Models and Justification for using Large Computers

Careful selection and efficient use of a farm machinery system is increasingly important because of the rapid rise in cost of both equipment and fuel. Crabtree (1978) quoted Nix's view at the 1978 Oxford Farming Conference that during the period 1970-77 for a 200 ha, mainly arable farm, costs had risen by 490 per cent or an average annual increase of 23 per cent. In support of his argument, he quoted the data supplied by the Department of Industry which showed an average rise of 20 and 27 per cent on tractor purchase prices for the periods 1970-75 and 1975-77, respectively. These price rises are around the same level for other forms of farm machinery (Crabtree, 1978).

For the year 1975, Cottrell and Audsley (1976) calculated that the average purchase price of tractors in the British market was around £50/kW. The comparable figure for 1979 was £115/kW based on figures in Power Farming 1979.

This shows an increase of 130% over the period of four years or an annual average increase of 32.5% which is considerably higher than the ones suggested by Nix and the Department of Industry. In the case of fuel costs, the price of tractor diesel has risen from 6.51 pence/litre in 1975 to 15.46 pence/litre for deliveries of 2250 litres for the Borders Region in Scotland, which is an overall increase of 137% in 5 years and an average annual increase of 27.4% (BP, 1980).

Like the tractor price rise (Crabtree 1978), the fuel price rise for the period 1978-80 considerably exceeded that for the period 1975-78 (Figure 3.1).

With rapidly rising costs and dwindling profit margins, there is a greater need to avoid machine down-time and power wastage by efficiently scheduling machine operations and by carefully choosing suitable machine type and size in conjunction with the proper power units. This can be achieved by referring to previous personal experience or that of others in small and simple farms, or by using different management aids such as published data, case studies and machinery scheduling or selection programmes in the case of big and more complex farms. Information on performance, costs and reliability of different machines in average working conditions can be obtained from the Agricultural Engineering Year Book (ASAE,1980). Price guides are published in the Agricultural Press. Weather data is available directly from local meteorological offices or from their publications. Applying these data, machine selection advice can be obtained from either simple procedures, with the aid of small calculators and mini computers (Hunt, 1974) or extensive selection models which require programming experience and main frame computers. Although access to large computers is more restricted and more expensive, nearly all of the complex selection procedures require their use.

Apart from the availability, however, there is also farmer's resistance to the use of big computational aids because of their costs. In a survey carried out by Erickson (in Hunt 1974) to assess the willingness of Illinois farmers to use a computer assisted management programme developed by him to solve their machinery management problems, 91% of the farmers favoured small computers while 60% and 13.5% were willing to use medium and large computers, respectively.

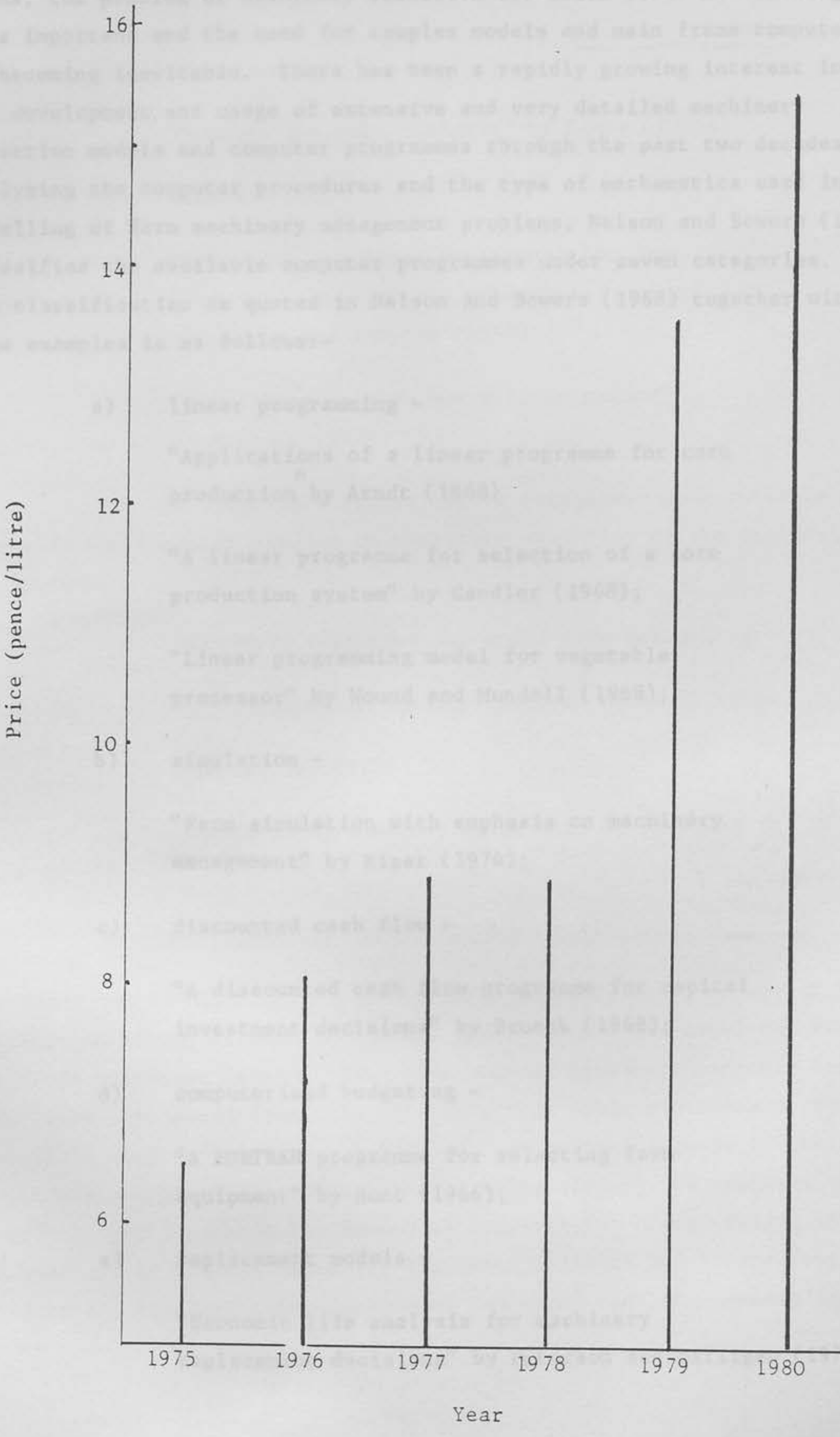

FIG. 3.1: Price of tractor diesel for years 1975-1980.
(Data supplied by B.P. St Boswells, August 1980).

With the world trend towards large and more highly mechanised farms, the problem of machinery selection for small farms is becoming less important and the need for complex models and main frame computers is becoming inevitable. There has been a rapidly growing interest in the development and usage of extensive and very detailed machinery selection models and computer programmes through the past two decades. Analysing the computer procedures and the type of mathematics used in modelling of farm machinery management problems, Nelson and Bowers (1968) classified the available computer programmes under seven categories. The classification as quoted in Nelson and Bowers (1968) together with some examples is as follows:-

a) linear programming -

"Applications of a linear programme for corn production" by Arndt (1968)

"A linear programme for selection of a corn production system" by Candler (1968);

"Linear programming model for vegetable processor" by Wound and Mundell (1968);

b) simulation -

"Farm simulation with emphasis on machinery management" by Kizer (1974);

c) discounted cash flow -

"A discounted cash flow programme for capital investment decisions" by Brueck (1968);

d) computerised budgeting -

"A FORTRAN programme for selecting farm equipment" by Hunt (1966);

e) replacement models -

"Economic life analysis for machinery replacement decisions" by Peterson and Milligan (1976);

"A practical approach to vehicle replacement" by Ayres and Waizeneker (1978);

f) cost records -

"Methods for cost analysis" by Kampe (1971);

f) others -

"Operating procedure for simulation farm planning - Monte Carlo method" by Donaldson and Webster (1968);

"Farm planning with Monte Carlo method" by Everett (1970).

For the literature review, it is considered more suitable to classify the computer studies on machinery selection by the application as follows:

- Machinery selection for whole farm operations
- Machinery selection for specific tasks or crops
- Tractor selection

In the forthcoming section, these will be examined in more detail.

3.3 <u>Machinery Selection for Whole Farm Operations</u>

Singh and Holtman (1977) developed a computer model to select an optimum machinery system for a mixed arable farm. The model was based on field operation calendar date constraints, machinery capacity relations and field work conditions. In this work, the optimum procedure, which is generally used for machinery selection, was omitted because of the need to reduce computational difficulties. Alternatively, he proposed an algorithm which reduced the amount of computations whilst taking into account all of the operationally important criteria and constraints. Despite all the advantages mentioned, the model uses very generalised and over simplified block data. For example, the assumption of a fixed value for the plough draught requirement or a fixed depth and width of cut or a fixed travel speed and tractive efficiency produces a lack of flexibility for the programme because these variables are extremely dependent on the type and moisture content of soils of individual farms. It is for this reason that Finney (1978) suggests that an accurate estimation of a machinery system for a farm is a matter for subjective judgement by the farmer or farm manager and should be based on past experiences with those machines on that particular farm. Machinery selection should take into account the available facilities on the farm and possible use of contractors.

A decade earlier, Hunt (1966) mentioned the need for selection of farm machinery on an individual farm basis because of the agronomic, enterprise and topographic variability of one farm from another. With this object in mind, Hunt (1966) had developed a model which was adaptable to a large number of field conditions and machine variations. Despite all these efforts, the model had two major shortcomings: a) the need for extensive and detailed input data and, b) excessive simplifying assumptions on estimation procedures. These requirements increased the amount of time and cost involved in the preparation of data and created limitations on adaptability of the model to areas where the data is less comprehensive.

The model selects the machinery system on an economic basis of minimum cost. The annual cost of each machine is related to its pto power in case of tractors and effective width of operation for other machinery, (Hunt 1963). By using a simple algebraic minimisation procedure, Hunt (1973) determined the minimum annual cost for a given size of tractor and implement.

Kizer (1974) studied the application of a simulation method to farm machinery management problems and compared it with a partial budgeting procedure stating their shortcomings with respect to machinery selection problems. He used the agricultural business simulator developed by Hutton and Hinman (1969) to model pertinent variables of a farm machinery system and find definitive answers for machinery management problems in general and machinery selection problems in particular. These pertinent variables were defined as the cropping programme, cropping area, work rate, machinery system size, machine combination and cost of owning and operating machinery. Although the importance of timeliness of operation was acknowledged, it was not evaluated in this study.

Unlike Kizer (1974), Jose (1971) in his computer model concentrated on the effect of rainfall variability and importance of capturing the advantages of timely operations with respect to plant development. In this model, an algorithm was used to quantify the costs and returns from alternative machinery systems over the expected life of the machinery combination. He analysed five machinery components including cultivation, planting, hay and corn silage harvesting equipment for four various areas and pointed out the need for possible improvement of the programme to upgrade its ability to analyse more machinery components and enterprise sizes.

Hughes and Haltman (1974) also looked at machinery complement selection, emphasising on time constraints and timeliness of farm operations. He developed a machinery complement selection model and a computer programme to implement the model. In this model, power requirements of field operations, tractors required to produce that power and machine sizes suitable for these tractors are selected and their annual use, operating costs and energy costs are calculated. The model is proposed as an alternative model for the standard models suggested by Agricultural Engineering Year Book (ASAE 1971) and Bainer, et al (1965). The adopted procedure analyses the effect of factors influencing the power requirement of different field operations and evaluates the quantitative importance of each factor upon the size and type of the machinery system. The two main factors affecting the power requirement of the field operations considered in this programme are the amount of the work to be done and the time available for that work.

Apart from size selection this programme sets up a work schedule for farm operations as well as calculating their cost, the use of general draught data and fixed work day criterion for soil workability made this programme unsuitable for our purpose.

Von Bargen and Hines (1973) developed a machinery complement programme which uses methods suggested by Bowers (1970) and Hunt (1968) to determine salvage values of machines and timeliness penalties of the critical farm operations, respectively.

The straight-line method was used to determine depreciation but, due to the structure of the programme, other methods of estimating depreciation can be used. The model also has an error message routine which enables the operator of the programme to diagnose possible mistakes in the programme. The bulky input data for this programme is an effective determent to its more general use.

3.4 Machinery Selection for a Specific Task or Crop

In some cases, a machinery system is used to perform the same task for different crops (e.g. sowing peas or sugar beet) whilst in other cases, the same crop may require a different machinery system to accommodate alternative conservation practices (e.g. corn for silage or grain) cropping techniques, topographic variations and climatic changes. In consequence, mathematical models and computer programmes refer to a specific task or a specific crop.

3.4.1 Specific Task

Examples of programmes which deal with a special operation or machine are those developed for tillage operations, and harvesting of forage, cereal and industrial crops.

Tillage Operation

Zoz (1973) analysed a machinery system for tillage operation and identified six essential steps in the optimum selection of a tractor-tillage system:

1. prediction of tractor performance;
2. prediction of implement draught requirement;

3. matching of the tractor and implement;

4. prediction of productivity;

5. estimation of tractor and implement investment costs;

6. fixed and variable cost determination and optimisation.

The same broad approach has been adopted for the present study although there have been major changes in detail.

For predicting tractor performance, Zoz (1973) used the mathematical and graphical methods he had developed in his previous work (Zoz 1972). Implement draught requirement was related to the square of actual travel speed and tractors were matched to implements by comparing the pull produced by the tractor and the draught required for pulling of a certain implement. The work rate of the implement was predicted from the speed of operation and the width and field efficiency of the implement. The cost of the tractor was related to its power and speed of travel, while the cost of the implement was calculated from the width of the implement and the travel speed. A year later, he modified his work to make it applicable to UK conditions (Zoz 1974).

Cottrell and Audsley (1976) extended the work done by Zoz (1974) to determine the costs for a rotary digger - a new experimental cultivation equipment which is driven by the tractor p.t.o. - as well as for other conventional draught implements. Power, operating speed and weight on the driving wheels of the tractor was related to the implement width required to operate a combination of tractor and mouldboard plough, chisel plough and rotary digger. In a later work, Audsley (1976) described a linear programming model to determine the men and machinery requirements of a maximum profit cultivation, drilling and harvesting system. Timeliness of these operations was evaluated to minimise the pissible conflict of their demands for scarce resources of men and machinery in critical seasons. By means of this model, Audsley (1977) determined the economics of different cultivation techniques and compared them with the technique using the rotary digger.

An analysis of soil-tractor-implement (Tillage) systems was carried out in America by Woorhees and Walker (1977). Tractor performance was predicted by means of an equation proposed by Wismer and Luth (1972 a) which takes into account the soil penetrometer resistance as a measure of soil strength. The equation proposed by Sö hne (1960) to predict plough draught requirement was modified to incorporate the effect of the variations of the soil moisture content, ploughing speed and plough specifications on the forces affecting plough draught. In a study of tractor-plough systems to extend trafficability limits of soils, Gee-Clough (1977) used empirical equations from his previous work, (Gee-Clough et al 1977e) to model tractor-plough performance for tillage-operations. Procedures used in this work were found to be suitable for the purpose of the present study and with some variations, were adopted in the programme. Further details of the development, use, advantages and limitations of these procedures is given in sections 4.1.

Forage Harvesting

For forage harvesting and conservation systems, Boyce et al (1979) applied the simultation model developed by Parke and Dumont (1979) to evaluate the effects of conservation methods on hay value. This model was designed to study the effect of machine performance on the nutrient content of conserved forage but its scope was extended to facilitate the assessment of the effects of crop growth characteristics, climatic variations and management policy as well as machine performance. This complements the studies carried out at National Institute of Agricultural Engineering on forage conservation systems by Parke et al (1976), Parke and Dumont (1977) and Dumont and Parke (1978).

Similar researches were conducted at Edinburgh School of Agriculture. Witney and Beveridge (1975), in an attempt to identify the best mechanisation system for silage making, compared the economics of four silage making systems and quantified two indirect cost items of timeliness penalty and dry matter losses during the period from cutting and feeding in addition to mechanisation costs in terms of value of beef output foregone. Systems studied in this work are:

- a two man direct-cut system;
- a three man wilting system with double-chop harvester;
- a four man wilting system with a precision-chop harvester.

They concluded that, of these systems for operations up to 20 ha/a a flail harvester system proved to be the cheapest, but for larger farms with 20-40 ha/a and above 40 ha/a, a double-chop harvester system and a precision chop harvester system were cheaper, respectively.

In another study, Witney and Morrison (1977) compared the economics of four hay making systems with one silage making system. Methods chosen were:

1. barn-drying traditional bales, baling at 40% moisture content;
2. barn-conditioning traditional bales, baling at 30% moisture content;
3. barn-conditioning big square bales, baling at 30% moisture content·
4. field curing.

The conclusion from this study was that the silage feeding gave the highest value of livestock output. Barn-dried hay, barn-conditioned hay and field-cured hay were the second, third and fourth best techniques, respectively. Mathematical techniques used in these studies were simple algebraic cost minimisation methods to identify a minimum cost grass conservation system with maximum livestock output. These studies were based on an earlier study by Dalton and Kettleborough (1973) which was done on the selection of silage making systems for milk production, even though there were some variations on the techniques and methods used for the original work.

Jeffers and Staley (1968) utilised the cost minimisation procedure in association with available days for hay making developed by MacHardy (1965) and Hunt (1963) to select a minimum cost forage machinery system. To obtain the number of available days for hay operations from local meteorological data and a workday criterion, procedures suggested by Brooks and Carruthers (1953) were used.

Cereal Harvesting

Of all the harvesting systems, that for cereals is by far the most important. Buchele (1976) analysed the economic benefit gained from using efficient harvesting systems and compared it with the increasing of the farm area in order to improve the farm's cash flow. Philips and O'Calaghan (1974) developed an interacting computer programme in FORTRAN lV language to study the effect of many major variables upon the total cost of cereal harvesting systems. Variables identified in this study were crop variables such as timeliness and cutter bar losses; weather; economic variables such as machinery, field, maintenance and labour costs; and machine variables such as performance characteristics and work rates.

In a current study at the National Institute of Agricultural Engineering, Boyce and Rutherford (1972) developed a deterministic cost model which is concerned with the problem of selection and operation of combine harvesters. Factors affecting the total harvesting costs identified in this work, were similar to those identified by Philips and O'Calaghan (1974). In contrast to the above models which require extensive computing aids, Peterson (1970) developed a simple method for the selection and economic analysis of cereal harvesting systems. This model is manually operated and can help the user to identify profitability of combine harvester use, marginal conditions for combine harvester investment and operations and the level at which ownership would be preferable to custom work or joint co-operative operations. Although this model is designed for North America it can be applied to anywhere in the world because of its simplicity and flexibility.

Harvesting Industrial Crops

Although the economic analysis of harvesting systems for industrial crops has received less attention than those for cereals, there are some computer programmes or mathematical models available for high yielding crops such as cotton, sugar beet, sugar cane and soy-beans. Different mathematical procedures have been utilised to solve problems of mechanising the harvesting of these crops.

A mathematical optimisation method was used by Sanders and Lalor (1972) to optimise machine/size/crop/area relationship for cotton. Dynamic programming has also been suggested as a useful means of solving farm machinery management problems. Sowell and Link (1971) applied dynamic programming models on formulations of machinery replacement problems for cotton picking. This formulation includes the expected costs resulting from probable machine breakdown as well as the usual costs. Another example of the application of dynamic programming is a model developed by Morey et al (1972) to optimise corn and soybeans harvesting systems. The model can be transformed into a multiple purpose model and used to optimise other harvesting systems. Simulation is also used as a technique to identify efficient harvesting machinery systems. Carpenter and Brooker (1972) developed a simulation model to determine the minimum cost harvesting, drying and storage system for corn growning operations of various sizes. Shukla et al (1971) simulated harvesting, loading and transportation of sugar cane in a computer programme to analyse the effect of each of these operations on the economics of the whole system and to recommend the most suitable size, type and number of harvesters, loaders and carts.

Dalton and Coney (1973) in a search to identify the best harvesting machinery system for sugar beet, used Capacity Cost Curves to compare the following systems:

- 5 or 6 row multi-stage harvester;
- 5 row-stage harvester;
- a self-propelled single row tanker;
- a tractor-drawn single row tanker;
- a tractor-drawn side-delivery harvester.

The conclusion drawn from this study was that for farms up to 20 ha (50 acre), the single row tanker was the cheapest machine and for areas between 22-27 ha (55-60 acre), a two-stage machine has a small cost advantage over the others. For farms larger than 30 ha (70 acres), the three-stage harvester was the most economical one. In addition to machinery selection, the model identifies the effect of the time and cost of harvesting operations and the area to be harvested upon the selection of harvesting machinery and its costs.

3.4.2 Specific Crops

Due to importance of maize studies have been conducted on economic analysis of corn production systems in North America, Candler (1968) and Arndt (1968) applied linear programming on selection and cost analysis of a corn production system, respectively. Arndt (1968) described The Automatic Corn Budget which was developed at Purdue University by Candler (1968) as a tool to solve management problems for barn production systems. In another study, Frisby and Bockhop (1968) applied the mathematical models suggested by Link (1962) to compare ten machinery systems in order to identify the best machinery system for a corn production farm. Burrows and Siemens (1974) studied this problem with wide scope and developed a computer model to determine the least cost, number and size of machines required for corn - soybean farms.

3.5 Tractor Selection

During the early phases of agricultural mechanisation, tractors were introduced to replace animal power and thus, were designed for draught operations with a relatively low power output. The demand for high powered tractors was created by the increasing cost of labour and the amalgamation of farms into larger units. As tractor power size increased, the design became more complex so that the engine power could be used not only for traction but also at the P.T.O. and hydraulically. In a study carried out in Oklahoma, Bowers (1980) found that in 1935, a tractor with 25 kW at the drawbar was considered to be a big tractor. By contrast, in 1972, 37% of the farm tractors sold in that region were rated at 80 kW P.T.O. power or greater. The economic climate in the U.K.

is encouraging a similar trend towards large tractors but the problems of optimisation of tractor power has received much less attention in this country. This lack of interest is mainly attributed to the following reasons (Witney and Oskoui 1979):

a) the marginal cost of extra engine capacity is low;

b) there is little objective data on soil damage;

c) there is over-sensitivity to bad weather.

The demand for high powered tractors has affected the pattern of engine design and high power density engines (high power in a small package) have been developed by introduction of turbocharging and intercooling systems. High power density engines also retard the rate of engine cost increase (Kress and Koenigsaecker 1976).

Although the market trend is towards big tractors, they are not always economically justified. On some occasions, a small tractor can be more efficient and useful than a large one, but the complexity of the choice cannot be resolved without recourse to some form of selection programme. The broad approach adopted for these selection procedures is similar to that for machinery selection for tillage operations which is:

a) prediction of draught of different implements;

b) prediction of drawbar pull available;

c) properly matching the implements with tractors;

d) prediction of time required to complete the operation;

e) prediction of time available for farm work;

f) estimation of cost;

g) selection of best size and number of tractors.

Bowers (1980) used the same procedure to develop a selection method for big tractors as for his tillage machinery programme. Hunt (1971) also examined the problems associated with the selection and management of big tractors. In contrast with his previous studies, (Hunt 1963,1966), this appraisal included a mathematical model of tractor performance as a constraint in addition to existing economic, operational and power constraints. In a more comprehensive study by Witney and Oskoui (1979), tractor power was related to soil moisture content, soil workability, and available workdays by using cone penetrometer as a measure of soil strength. This study will be discussed in greater detail in chapter 4.

Chancellor, (1968) also departed from the general procedure by categorising tractor costs in three sections of fixed costs, energy costs and time costs, as opposed to the usual two category of fixed and variable costs. He also developed a procedure to optimise tractor size for contractor owned tractors as well as farmer owned ones. In this model the effect of soil type and physical conditions has not been taken into consideration regardless of its importance, especially where heavy draught works are practised.

3.6 Machinery Replacement

A machine is usually replaced by another one because:

a) its physical life is ended;

b) its economical life is ended;

c) it is obsolete;

d) or other reasons, such as taxation, personal desire .....

Replacing an existing machine when it is worn out or unable to perform its expected duties in a satisfactory manner due to a major breakdown with a newer one, is a very common practice, but is not an ultimate procedure. Some farmers do not favour retaining a machine until the end of its physical life. Instead they prefer an early replacement in conjunction with negotiations for a satisfactory trade-in value or they may conclude that retention of the machine beyond a certain year is no longer economical. In other words, the economic life of the machine is over. In some other occasions, the machine is neither non-operational nor uneconomical but the owner favours the replacement of the machine by a more advanced one because the new machine is more reliable and functionally superior. This situation is defined as obsolescence. There are some other factors which affect a replacement decision. It is very difficult to identify these factors and assess the extent of their effect on machinery replacement decisions. Examples of these factors are taxation, bargain buying and prestige buying.

An efficient replacement decision should consider all the relevant factors and aim for an optimum replacement policy. This objective has been approached by many researchers and computerised models have been developed to determine an optimum machinery replacement policy for agricultural and industrial machinery. Dunford and Pickard (1961) used a graphical method to determine an optimum replacement policy for agricultural machinery. They suggested that the best time for replacing farm machinery is when the average rate of holding cost (a term introduced by Fox (1957), which includes the initial and repair costs of a machine) per unit of working life is at a minimum. An arithmetic minimisation procedure was used to calculate the replacement interval.

Scarborogh and Hunt (1973) defined the best time of replacing of farm machinery as a point at which operating costs (sum of capital cost, repair and maintenance costs and the costs of obsolescence) of machinery per unit of usage time is at a minimum. They developed a procedure based on methods used by Bowers and Hunt (1970) and initiated by Larson and Bowers (1965), to obtain the optimum replacement time for agricultural machinery. This method and a scheduling procedure were used to complete the two machinery programmes which had been developed by Hunt (1966,1971). Boyce et al (1976) and Jardine et al (1975) adopted a similar concept to tackle machinery replacement problems. The only departure from the model by Scarborogh and Hunt (1973) was that the term "operating costs" used by Boyce et al (1976) did not include obsolescence costs. Both these models took into the account the effect of inflation and interest rate on the replacement policy. Costs of fuel, oil, shelter and labour were excluded from the calculation of operating costs in all of the works which have been reviewed so far. These costs were assumed to be constant and had no effect on economic life of machinery. In a study by Peterson and Miligan (1976) the concept of economic life analysis was used to determine the best replacement time for agricultural machinery. A computer programme was written to carry out the calculations and it applied to a potato harvester as an example. Ayres and Waizeneker (1978) also used this concept and analysed the data collected at the London Borough of Hammersmith to develop a simplified approach to vehicle replacement. This method did not take into account the timing of the receipts and payments, as a result the life of a vehicle as determined by this formula is not optimal. A better measure of the optimum life is by using the discounted cash flow method (Friedlander 1979). This theory was adopted for the purpose of the current study and the equations developed by Boyce et al (1976) were utilised in the development of the computer programme.

3.7 Tractor Performance

The need for full mechanisation of farm operations and the amalgamation of small farms into larger units inevitably increases the dependence of agricultural operations on fuel energy as the cost and shortage of labour increases and as the demand by the processing industries for bulk production of raw materials rises. The draught operation as a single item consumes the highest proportion of energy used on an arable farm. This energy is largely used in the form of drawbar power by transmitting the engine power through a traction device to the ground. This process is referred to as traction. Gill and Vanden Berg (1967) defined traction as 'the force derived from the interaction between a device and a medium that can be used to facilitate a desired motion over the medium.' In this study, wheels will be considered as the traction and transport devices instead of the whole vehicle so that the terms 'tractor performance' and 'tyre performance' are considered synonomous.

Although there can be a substantial energy loss from the engine to the wheels due to inefficiencies in the power production and transmission processes, these losses are assumed to be constant for a given tractor and independent of the terrain on which the vehicle is operating. In this study, the emphasis is placed on the evaluation of energy lost by soil-wheel interaction. The efficient choice of a tractor/tyre/weight/terrain combination can cause a substantial fall in the financial loss which can occur due to excessive slip and soil damage. Based on data from the Nebraska Test Reports, Gill and Vanden Berg (1967) stated that this loss would amount to £20m ($42m) annually in the U.S.A. An understanding of traction mechanics and an analysis of major factors affecting this process can provide a useful guide to the selection and management of traction devices. Brixius and Wismer (1978) used a simplified soil-wheel model shown in Figure 3.2 and explained single wheel operating states which can be considered to progress from towed through self propelled, to driven as a function of increasing wheel slip. They quoted that a towed wheel is unpowered; axle torque is zero, neglecting bearing friction. For a self propelled wheel, pull or net thrust is zero with the applied driving torque simply overcoming rolling resistance of the wheel. If a wheel must develop a finite pull, the wheel passes into the driven wheel state where slip is positive. This state is the main concern of the current study and factors affecting and methods of prediction of performance of a driven wheel will be studied in the following section. Two very commonly used measures of tractive performance are tractive efficiency which is the drawbar power divided by the total tractor engine power and the coefficient of traction which is the drawbar pull divided by the weight on the tyre.

3.7.1 Factors Affecting Tractor Performance

The factors affecting the tractor performance can be categorised under four major sections:

1. tractor - weight and shape or design;
2. tyre - dimensions, lug height and inflation pressure;
3. terrain medium - moisture content, slope, compaction and surface cover;
4. speed - travel speed and travel reduction.

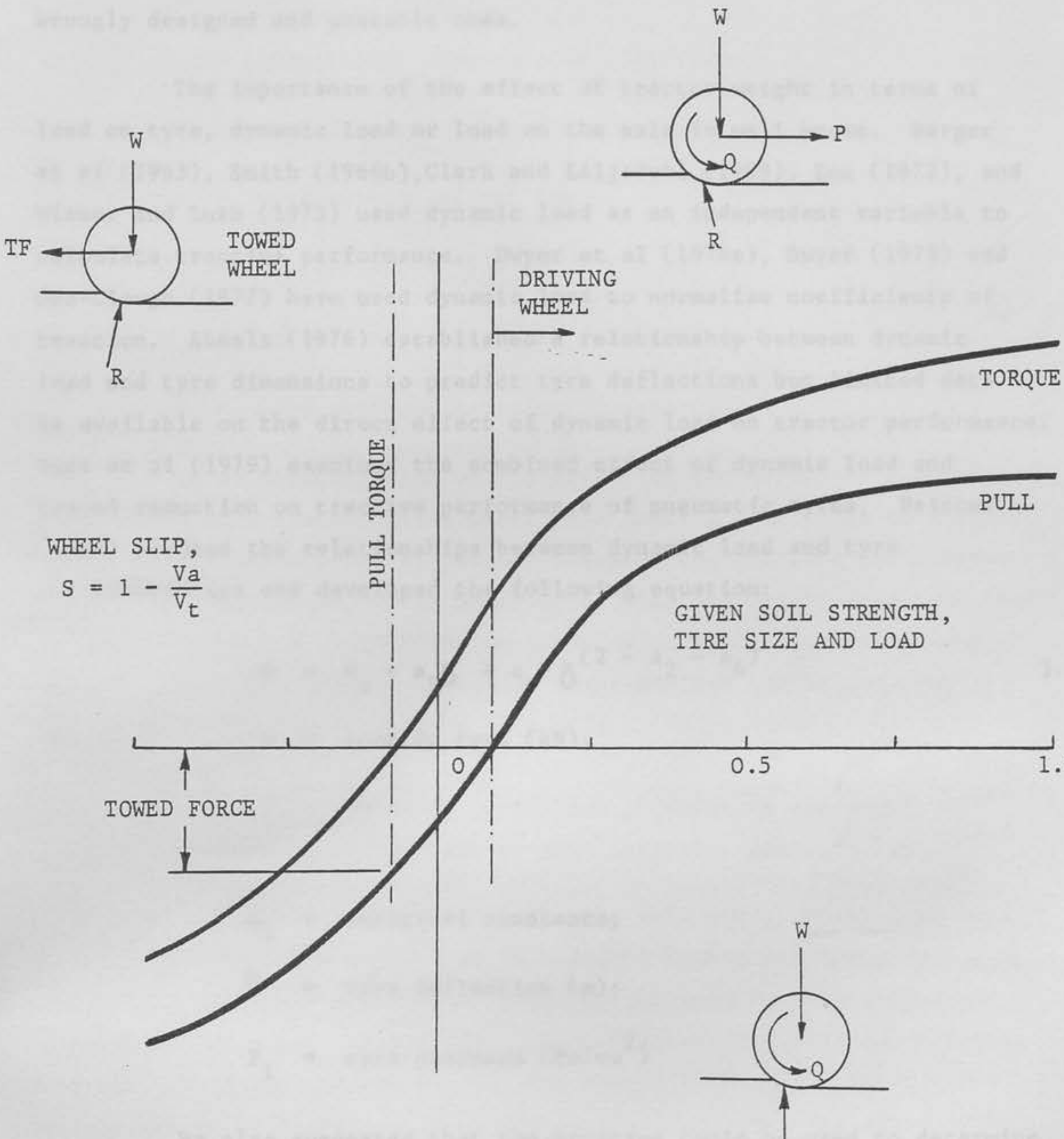

FIG. 3.2: Pull/Torque/Slip relation, wheels on soil.
(Brixius and Wismer 1978)

Shape and design has more effect on tractor stability and manoeuvrability than on tractive performance but better designed and more stable tractors can be more efficient, especially on slopes, than wrongly designed and unstable ones.

The importance of the effect of tractor weight in terms of load on tyre, dynamic load or load on the axle is well known. Barger et al (1963), Smith (1966b), Clark and Liljedahl (1969), Zoz (1972), and Wismer and Luth (1973) used dynamic load as an independent variable to calculate tractive performance. Dwyer et al (1974a), Dwyer (1978) and Gee-Clough (1977) have used dynamic load to normalise coefficients of traction. Abeels (1976) established a relationship between dynamic load and tyre dimensions to predict tyre deflections but limited data is available on the direct effect of dynamic load on tractor performance. Burt et al (1979) examined the combined effect of dynamic load and travel reduction on tractive performance of pneumatic tyres. Painter (1980) studied the relationships between dynamic load and tyre characteristics and developed the following equation:

$$W = W_o + a_5\delta + a_6 P \delta^{(2 - a_2 - a_4)} \qquad 3.1$$

Where: W = load on tyre (kN);

W_o = value of load which produces no measurable deflection at zero inflation pressure (kN);

a_i = empirical constants;

δ = tyre deflection (m);

P_i = tyre pressure (Pa/cm^2)

He also suggested that the equation could be used to determine the load carrying capacity of a tyre with known dimensions. Komandi (1976) also developed an equation to determine the load carrying capacity of a tyre on a concrete surface but used more tyre dimension data and was more specific. The equation is as follows:

$$W = \frac{(C_2h)^{1.18}}{bC_1} \left(\frac{b^{1.7}d^{0.43}P_i^{\,0.6}}{C_2}\right) \qquad 3.2$$

b = tyre width (cm);

C_1 = coefficient depending on tyre design;

d = tyre diameter (cm);

h = tyre section height (cm);

C_2 = coefficient = $15 \times 10^{-3}b + 0.42$·

P_i = inflation pressure (kp_a/cm^2);

W = load carrying capacity of tyre (kN)

In an investigation of the effect of lug height on tractive performance of a tractor drive wheel tyre under a wide range of field conditions, Gee-Clough et al (1976a) compared the tractive performance of five 13.6-38 tractor drive wheel tyres with lug height from 0 to 75mm. From the standpoint of traction performance, they concluded that lug height beyond 20mm was not justified under British conditions, but it was required to ensure adequate tyre life.

The terrain on which a tractor wheel is operating has a drastic effect on the performance of a drive wheel tyre. Bowers (1980) stated that the amount of tractor power lost at the soil tyre interface can vary from 37.5% on firm land to 52.4% on a soft soil. Power loss on a tilled soil can be as much as 44.6% assuming that the drive wheel dimensions were kept constant, tractor weight must vary to obtain a constant drawbar pull from a given tractor at a given slip on different terrain. Williams and Van Syoc (1968) stated that static drive wheel weight should be increased from 4000 kg (9000 lb.) for irrigated adobe soils, to 4500 kg (10500 lb.) for corn belt soils and to as much as 9500 kg (21000 lb.) for grassy marshland soils to obtain an acceptable drawbar pull of 22 kN (9700 lb.) from a 75 kW (95 hp) tractor at 15% slip. These variations can be attributed to the changes in the physical and topographical characteristics of the terrain such as:

- medium which constitutes the terrain (soil, cement, etc.);
- moisture content;
- slope;
- compaction;
- surface cover.

The direct effect of the type of medium which constitutes the terrain has been studied by many researchers (Bowers, 1980; Hunt, 1971; Zoz, 1972, 1973, 1974; and Williams and Van Syoc, 1968). Some have involved this factor indirectly in their calculations and used a measure of strength (cone penetrometer resistance or shear resistance) which is unique for every medium. (Gee-Clough et al 1976b, 1977a and 1977b; Gee-Clough 1977 and 1980).

Although moisure content significantly affects the tractive performance of a tractor operating on agricultural soils, its relevance has been ignored by some (Zoz 1972, 1973 and 1974), and emphasised by many others (Wismer and Luth, 1973; Woorhees and Walker, 1977 and Gee-Clough, 1980). In the latter studies, cone penetrometer resistance which, according to Wells and Treesuwan (1977), Woorhees and Walker (1977) and Witney and Oskoui (1979), is strongly affected by soil moisure content has been used as the independent variable in the prediction of tractive performance of tractors.

Tractors operating on flat land will produce far greater pull than those operating on slopes. A tractor operating at 28% slope (16 deg.) will use 50% of its available tractive effort to propel the vehicle up the hill. Side slope can also reduce tractive efficiency of a tractor. This can be improved by using larger tyres plus additional ballasting or by fitting dual tyres. Over-sized and lightly loaded tyres are the most effective (Williams and Syoc, 1968).

Another consideration which affects tractive performance of a drive wheel tyre is the level of compaction of the terrain on which the tyre is operating. In an attempt to compare the tractive performance of a tractor driving wheel during its first and second passes in the same track under typical agricultural conditions, Dwyer et al (1977) concluded that the tractive efficiency of a tyre running in the track of a similar tyre carrying the same load will be 5% higher than that of the first tyre.

Travel speed also affects tractive performance of drive wheel tyres. The limited data available suggests that higher tractive efficiency can be achieved at higher speeds. Gee-Clough et al (1978) compared the tractive performance of a tyre at 6.4 km/h and 3.2 km/h speed in thirty one different field conditions. The result was an average increase of 4% in the coefficient of traction for one year and 3% increase for the second year. Maximum tractive efficiency also increased at the rate of 3% for the first year but remained unchanged for the following year.

3.7.2 Prediction of Tractor Performance

Various approaches have been adopted to model the tractor-wheel-terrain relationships (traction) and different procedures have been developed to predict tractor drawbar pull and tractive efficiency. These methods can be differentiated by their approach to soil strength assessment under the following four categories:

i) plasticity and yield criteria

ii) pressure sinkage relationship

iii) cone index values and mobility numbers

iv) regression analysis

First is the use of formal methods of plasticity to define the soil failure zones ahead and behind the wheel and hence to calculate wheel forces. Nowatzki and Karafiath (1974) developed a theory of soil wheel interaction based on plasticity theory and a general representation of Mohr yield criterion. A computer programme was developed to facilitate calculations. This model was restricted to the prediction of the performance of a rigid wheel on sandy soil. Rutledge and McHardy (1968) adopted the equations developed by Nicols (1932) and based on Coulomb's theory to relate soil shear strength to tractor pull. The soil parameters used in these equations are the upper plastic limit, moisture content, plasticity number, clay content and soil confining pressure. This equation does not give an accurate estimate of shear strength for non-plastic soils, i.e. soils with a low clay content. Dwyer et al (1974b), in an attempt to obtain empirical relationships between tractive performance of tyre and soil shear strength, related coefficient of traction at 20% slip to tyre inflation pressure, soil cohesion, angle of soil internal friction and soil-rubber adhesion and friction. They concluded that neither the soil shear strength nor the interfacial shearing resistance provided a very satisfactory mean of predicting the coefficient of traction in the field. Another method utilising plasticity theory was suggested by Yong and Fattah (1975). They used the viscoplasticity technique developed by Yong and Webb (1969) to predict wheel-soil interactions and performance. The adoption of this technique was justified by the consistency of the predicted and measured data (Yong and Fattah, 1976). Their analysis also incorporated the finite element method developed by Perumpral et al (1971) as a numerical approximation procedure to predict sub-soil stresses and strains. The shortcomings of this method were acknowledged by the comment: "This method has suffered somewhat in view of the absence of corroborating and comparative physical measurements." Endorsing this reservation, Gee-Clough (1978) stated "closed solutions are not possible with this model and digital computers must be used to obtain a solution. This results in a cumbersome analysis which is not, as yet, suitable for practical applications."

The second approach to soil strength assessment forms an essential part of Bekker's (1956) traction mechanics. He proposed that plate sinkage tests were related to rolling resistance and that shear plate or ring tests were related to tractive force. This theory originally was proposed for rigid tyres. Shear stress at the soil wheel interface and relationship between wheel skid and wheel forces were not considered. Wills (1966) applied this theory to tracked vehicles and indicated that it provided a good basis for predicting tracked vehicle performance. Reece (1967) applied this theory to wheeled agricultural tractors. The model was extended to take into account the effect of tyre flexing (Bekker and Semonin, 1975), bulldozing resistance (Bekker, 1976) and skid and deep sinkage (Gee-Clough, 1976). Gee-Clough (1978) compared measured results for coefficient of rolling resistance, lift and drag with those predicted by Bekker's theory and concluded that this theory is only applicable to sandy soils with very narrow tyres.

The third method for relating the tractive performance of vehicles to measurements of soil properties is by means of the cone penetrometer developing mainly at the U.S. Army Engineer Waterways Experiment Station, Vickburg, Mississipi. This instrument is light (2 kg when made entirely from stainless steel), durable and can be operated by one man although a second man is required as a note-keeper. The term 'Cone Index' which will be referred to in this study is, according to Knight (1956), "an index of the shearing resistance of soil obtained with the cone penetrometer. The value is a dimensionless number representing the resistance to penetration into the soil of a 30° cone of 1.29 cm^2 base or projected area. The number, although considered dimensionless is actually kilograms of force on the dial divided by area of the cone base in square centimeters." Knight (1956) and Knight and Rula (1961) used this number as a mere indication of trafficability of soils for military vehicles. For satisfactory traction (movement of a vehicle from one specified point to another with least amount of motion wasted), the terrain must not only support the vehicle but also provide sufficient resistance so that thrust can be developed between traction device(wheels, track) and terrain with minimum slip. Cone index, by itself, is a good indication of the load carrying capacity of the terrain but does not give a good measure of its shearing resistance (Soane et al 1971a). Yong and Youssef (1978) devised an instrument which contains a vane as well as a cone to enable the dual measurement of both the shearing resistance of the soil and its deformation. In an earlier examination of the relevance of cone indices, Freitag (1965) included cone index in a dimensional analysis of pneumatic tyre performance, proposed a method of predicting tyre performance and applied to dry sand and saturated clay. He proposed non-dimensional numbers, for sand and clay soils which should be constant for each value of tractive performance number such as coefficient of rolling resistance, etc. In this analysis, he obtained the following relationship between tyre width (b) and diameter (d), load of tyre (W), and cone index (C):

$$\frac{d}{b} = \frac{K_1 CId^2}{W} \tag{3.3}$$

where K_1 is the constant of proportionality.

By re-arranging equatinn 3.3 to the following form:

$$\frac{1}{K_1} = \frac{CIbd}{W} \tag{3.4}$$

he termed the dimensionless number $\frac{1}{K_1}$ as clay number.

In a further study by the same author, Freitag (1966), the effect of tyre deflection (δ) and section height (h) was also taken into account and the following equation was developed:

$$\frac{(1)^{\frac{1}{2}}}{(K_1)} = \frac{CIbd}{W} \quad \frac{(\delta)^{\frac{1}{2}}}{(h)} \tag{3.5}$$

$\frac{(1)^{\frac{1}{2}}}{(K_1)}$ was termed combined clay loading-deflection number. In another attempt, Frietag (1968) used dimensional analysis to investigate the possibilities of developing a similar number for sandy soils. The result of this investigation was a development of a dimensionless number (K_2) which was called the sand number. The main departure in the development of this number from the previous clay number was the use of the cone index gradient (G) in place of the cone index itself (CI) in previous study. The resultant equation was:

$$K_2 = \frac{G(bd)^{3/2}}{W} \tag{3.6}$$

where K_2 was termed as sand number and is expected to be constant for each value of a performance number. In the same study, the effect of deflection and tyre section height on the sand number was also included and the sand mobility number was developed:

$$\frac{1}{K_2} = \frac{G(bd)^{3/2}}{W} \quad \frac{\delta}{h} \tag{3.7}$$

where $\frac{1}{K_2}$ is termed as sand mobility number. These numbers have been used by many researchers to model the drive wheel performance of vehicles. Melzer (1976) used the sand number to predict the pull produced and the power requirements for wheels operating in sand. He introduced another dimensionless number, namely, power number (PN) which was a function of torque (Q), active rolling radius of the wheel (Wra) and slip (s) as follows:

$$PN = (Q/Wra) / (1 - s) \qquad 3.8$$

and used this number to calculate power requirement for the wheels operating on sand.

Wismer and Luth (1973) utilised the clay number (equation 3.4) and developed a series of equations to predict the coefficient of traction (pull/weight) and tractive efficiency (output pull/input torque).

Zoz (1974) adapted this procedure in conjunction with the results of his own experiments (Zoz, 1972) to develop a tractor performance prediction chart which later on was used by authors like Hunt (1976) and Bowers (1980) in their machinery selection programmes. Woorhees and Walker (1977) also used the equations developed by Wismer and Luth (1973) to predict soil traction ability. Brixius and Wismer (1978) adopted these equations to evaluate the effect of slip on traction. By adding a further correction for the width/diameter ratio to the combined clay loading-deflection number (equation 3.5), Turnage (1972) produced a number now designated as the wheel mobility number (WMN) or the clay numeric as Turnage (1972) termed it.

$$WMN = \frac{C_I bd}{W} \quad \frac{\delta}{h} \times \frac{1}{1 + \frac{b}{2d}} \qquad 3.9$$

From a series of laboratory tests with a single wheel tester, Turnage (1972) concluded that the coefficient of traction for wheel tractors could be predicted with good accuracy using the wheel mobility number (clay numeric). In a further study, Turnage (1973) examined the possibilities for the derivation of relationships between tractor performance and wheel translational velocity by using wheel mobility number (WMN). In a very comprehensive study by workers at the NIAE to identify the factors affecting tyre performance and to evaluate the extent of their effects on overall tractor performance, WMN was used as an important variable from which the traction characteristics of drive wheel tyres and hence the overall performance of a tractor can be predicted. These studies are a continuation of the studies initiated by Hamblin et al (1945) at the Oxford Institute for Agricultural Engineering. Dwyer (1972) used results from the experiments with the NIAE single wheel tester, first introduced by Bailey (1954), to investigate the existing correlations between the traction characteristics of a drive wheel tyre and WMN. Another model of NIAE single wheel tester was designed and developed by Billington (1973) to provide more field results on the performance of tractors in the field. Dwyer et al (1974a) analysed the test results obtained by this apparatus and concluded that, in the field conditions where surface slipperiness is likely to affect coefficient of traction, WMN is not a good indicator of tractor performance. The coefficient of rolling resistance, however, can be satisfactorily predicted to within ± 0.05 at 95% probability from the values of WMN. Maximum tractive efficiency can also be predicted with the same accuracy from WMN. These predictions were more accurate than the predictions made from plate sinkage data except for the coefficient of traction which was poorer. To develop a handbook of agricultural tyre performance, Dwyer et al (1974b) used empirical relationships between the performance characteristics of tyres and WMN and predicted tractive efficiency, coefficient of traction, coefficient of rolling resistance and slip at maximum efficiency.

By means of these equations and some field test data Gee-Clough et al (1976a and 1977b) evaluated the effect of lug height on tyre performance. Effect of forward speed (Gee-Clough et al 1977a) aspect ratio (McAllister et al (1976), tyre dimensions (Gee-Clough et al 1976b) and compaction (Dwyer and Pearson 1977) can also be evaluated by means of WMN. WMN was utilised by Dwyer and Pearson (1976) to compare tractive performance of two and four wheel-drive tractors. Another comparison was made between performance of radial and cross-ply tyres (Gee-Clough et al (1977d) by means of equations developed by Dwyer (1972). These equations were used to optimise tractor-plough systems performances (Gee-Clough 1977, Gee Clough et al 1978 and 1977e). Another use of these equations was made by Dwyer (1978) to match tractor weight, tyre size and speed with available power. Accuracy of predictions made by this procedure was further confirmed by a study by Gee-Clough (1978) in which he compared the use of mobility numbers, plasticity or yield criteria plate sinkage relations for the prediction of tyre and tractor performance. Finally, Gee-Clough (1980) used WMN to obtain a guideline for tyre selection for agricultural tractors. In this work, Gee-Clough

(1980) reviewed all his previous studies and explored other possible uses for the equations based on cone index and WMN. These equations were accurate enough and required very simple, readily available and easily measurable data as opposed to other procedures which required complex data and extensive measurements. This was the motive which encouraged the adoption of this procedure for the current study.

The fourth and last procedure which only takes into account the effect of weight and travel reduction on tractor performance is the series of equations developed by Baileyand Burt (1976). These equations were empirical relationships derived from a regression analysis of their experimental results. Although they obtained a very good correlation between coefficient of traction, load on tyre and travel reduction, the use of very limited input data (weight and travel reduction) introduces doubts as to the general applicability of the model widely different soil and operating conditions. In spite of this shortcoming Burt et al (1978) utilised these relationships to evaluate the dynamic load distribution on the tractive performance of tyres operated in tandem. Another case for the use of these equations was a study by Burt et al (1979) in which he examined the combined effect of dynamic load and travel reduction on the performance of tyre operating in the soil.

3.8 Implement Performance

The tractor power demand at the p.t.o. or at the drawbar depends more on the types of implements in use than on the cropping programme. The amount of Specific draught required to operate an implement varies from a very low level of 0.3-0.8 kN/m (20-60 lb/ft) for a spike-tooth harrow in a light land, to as high as 9-17 kN/m (580-1140 lb/ft) for a mouldboard plough in a heavy land. According to Hunt (1973), of all the implements used on a farm, rotary-tillers and mouldboard ploughs consume the highest p.t.o. and drawbar power used on a farm, respectively. Despite the increasing interest in the use of non-conventional tillage tools and direct drilling, ploughing is still the most widely used method for seed bed preparation throughout the world. One of the objectives of the current study is to examine the factors affecting and the existing methods of predicting performance of a plough as a precursor to the tractor plough selection procedure.

3.8.1 Factors Affecting the Performance of the Implement

Gill and Vanden Berg (1967) classified the factors affecting the performance of a plough and its design under three main groups. These were factors associated with the shape and manner of movement of the plough and the initial soil conditions. Wismer and Luth (1972b) suggested another grouping which is more comprehensive and detailed than the one suggested by Gill and Vanden Berg (1967). In this classification also three main groups were identified which are, factors associated with the tillage tool, the soil, and the system. To obtain a clear picture of the tillage process and model tractor-plough performance, the effect of these factors on the draught requirements of a plough and, therefore, the power requirement of a farm will be studied in greater detail in the following section.

The depth and width of the tillage tools are two main factors associated with the first group having considerable affect on the amount of power required to pull the implement. Depth and width of the implements usually have been used as independent variables in the dimensional analysis of plough performance (Larson et al 1968); Reaves et al 1968; Wismer and Luth 1973, and Krastin 1973). Limited studies have been done to evaluate the effect of implement width and depth on its draught requirements. Payne (1956) quoted Zelenin's (1950) results in which he had found a perfectly linear relationship between draught and depth and width of a tine. To confirm these results, Payne (1956) carried out an experiment on three different soils both in the laboratory and in the field and found a slight departure from linearity in his results. He suggested that these departures were random and concluded that the draught of a soil cutting implement increased linearly with the increase of width and depth of the implement. The slope of the line was dependent on the soil type. The inclination to the direction of travel also has a marked effect on the implement draught requirements. Payne and Tanner (1959) found a dramatic increase on the draught of a tine, especially on sandy soil, when the rake angle of the tine was increased beyond 45°. The angle of vertical inclination has also been identified as an independent variable affecting plough draught in some analyses (Reaves et al 1968). The lateral directional angle of the plough mouldboard at the end is another pertinent variable which also has considerable effect on the plough draught (Söhne, 1960 and Larson et al 1968). Söhne (1960) found that the changes in gradient of the parabolic relationships between plough draught and travel speed is influenced by lateral directional angle of the plough at the mouldboard end.

The second group of variables which affect draught requirements of a tillage implement is the soil physical and mechanical properties. The most important of these are cohesion, bulk density, shear rate, cone penetrometer resistance, angle of internal shearing resistance and moisture content of the soil. Some of these parameters are strongly affected by changes in the soil moisture content. Cohesion and internal friction angle was found to be linear and bulk density a parabolic function of soil moisture content (Schafer et al 1968 and Camp and Gill 1969). Cone index has also been proved to be a function of soil moisture content (Wells and Treesuwan, 1977; Woorhees and Walker, 1977 and Witney and Oskoui, 1979). These parameters have been used as independent variables in dimensional analysis of tillage tool performances by many researchers (Larson et al, 1968; Yong, 1968; Reaves et al, 1968; Wang and Liang, 1970; Wismer and Luth, 1972a; Wang et al, 1972; Wang and Kwang Lo, 1973; and Krastin, 1973).

The third group of the variables which control draught requirements of tillage tools are those associated with the soil machine system. These are acceleration due to the gravity, coefficient of interface friction, adhesion and velocity. Gravitational acceleration and interface friction coefficients are used as independent variables in the modelling of the tillage tool performance. Velocity or speed of travel is regarded as the most important factor affecting draught of a tillage implement. It is sometimes used as a single variable in draught prediction equations. McEwen and Bedi (1951) from their studies concluded that the plough draught was a linear function of travel speed. Söhne (1960), Schlegel and Morling (1969), Wilkins and Coleman (1971) and Zoz (1974) found a parabolic relationship between plough draught and travel speed.

3.8.2 Prediction of the Implement Performance

Efficiently designing and using tillage implements can have a dramatic impact on power consumption and, therefore, on the cash return from an agricultural enterprise. From the figures supplied by USDA, Schafer et al, 1968, calculated that approximately 250 billion tonnes of soil covering about 160 million hectares are tilled in the United States alone every year. These operations require tremendous expenditure of time, labour and power and in many cases are inefficient. Many research organisations have devoted a considerable proportion of their funds and time to develop an efficient soil-machine system. As testing these systems for every soil and environmental condition is difficult, time consuming and costly, a good model which can predict the performance of the soil-machine system fairly accurately is of high value for both the designer and user of tillage machinery. Different factors have been identified as being pertinent to the performance of a tillage tool (Section 3.8.1) and various approaches have been adopted to evaluate the extent of their effects and to develop an efficient soil-machine performance predication model. Unlike traction, mathematical solutions to the problems associated with tillage operations are either very difficult or well-nigh impossible to obtain (Wang and Laing, 1970). Simple curve fitting (Schlegel and Morling, 1969; Wilkins and Coleman, 1971 and Zoz, 1973) analytical (Sohne, 1960 and Woorhees and Walker, 1977, etc.,) similitude (Wang and Laing, 1970, and Wismer and Luth, 1972a, etc.,) and other techniques have been used to quantify the force response relations for the soil cutting process.

Simple Curve Fitting Techniques

Implement draught requirements have been universally used as a measure of the performance of a tillage implement. Attempts have been made to solve problems of soil-machine systems by simply fitting equations to the experimental results to develop a draught prediction formula by many researchers. McEwan and Bedi (1951), in a series of experiments, suggested that draught of a plough increased linearly with the increase of width, depth and speed of ploughing. They fitted families of equations to their data but emphasised that more work was needed to derive a single prediction equation from these variables. Schlegel and Morling (1969) found that linear and up to fourth-degree polynominal equations as well as exponential relationships of speed can be employed to explain the results of their experiments and concluded that high degree polynominal equations, while giving the best fit of the experimental data, are difficult to calculate. Second-degree polynominal (quadratics) are sufficiently accurate. They dismissed the use of linear and exponential equations because of the lack of sufficient accuracy in comparison with the quadratics. Wilkins and Coleman (1971), Zoz (1973 and 1974) and Collins and Handy (1978) supported this idea and used quadratic equations in the form of equation (3.10) to predict plough draught from ploughing speed.

$$Z = K_1 + K_2 V + K_3 V^2 \qquad 3.10$$

Where: Z is specific draught of the implement, K_1, K_2 and K_3 are constants and V is the ploughing speed. They suggested that the draught calculated by means of these equations should be divided by the product of the depth and width of the plough (cross section) to eliminate the effect of these variables. In other words to calculate the draught of unit cross sectional area of furrow.

Analytical Techniques

These techniques either solely or in conjunction with other techniques have been used to study the performance of soil-machine systems. Ocock (1912) studied the factors affecting the draught of the plough. Rogers and Hawkins (1956) analysed the forces acting on general purpose, semi-digger and digger plough bodies in order to identify factors affecting the performance of a plough. In the same year, Payne (1956) initiated series of experiments to evaluate the effect of pertinent factors on the performance of simple cultivation implements. First he studied the effect of the mechanical properties of soil on the draught requirement of simple soil cutting tools. Then, in another study, (Payne and Tanner, 1959), he also examined the effect of rake angle on the performance of simple cultivation implement in order to develop a draught requirement prediction equation for simple soil cutting tools. This work was further studied by Tanner (1960) to cover wider ranges of rake angles and confirm the results of previous work by Payne and Tanner (1959). In a combined analytical and empirical study, Söhne (1960) studied the performance of different ploughs under different soil conditions. He utilised an equation developed by Goryachkin which resembled the one suggested by Zoz (1972), equation 3.10. This equation was further developed by Woorhees and Walker (1977) to incorporate the effect of soil moisture content. This was the basis of the equation developed and used in the current study. McKyes (1978) used analytical techniques to calculate draught forces of narrow tines.

Similitude Techniques

Similitude techniques have been widely utilised in various branches of science and engineering. A similar trend can be noticed in the study of the dynamic interactions of simple tools and tillage tools with agricultural soils. The justification for the use of small models usually involves economics and convenience. This may not always be the case in soil-machine systems, but, as the control of soil variables in the field can prove to be difficult due to climatic and topographic changes, the use of scale-models can be justified. As the general principles and broad aspects of similitude have been discussed in full detail in the literature (Murphy, 1950 and Zierep, 1971) they will not be discussed here. Four different methods can be applied to derive modelling laws in a similitude study - these are as follows:

a) dimensional analysis;

b) fractional analysis;

c) method of differential equations;

d) similarity by transformation of variables.

Dimensional analysis is developed from a consideration of the dimensions in which each of the pertinent quantities involved in a phenomenon is expressed. Pertinent variables are arranged in the form of dimensionless quantities or Buckingham π (pi) terms and qualitative relationships between them determined. These relationships then are combined with experimental procedures and made to supply quantitative results and accurate prediction equations. This method has been widely adopted to develop similarity laws in the similitude studies of soil-machine systems.

Fractional analysis is a method in which active forces in a system are identified, expressed by means of characteristic quantities and then used to form independent ratios of forces. These independent ratios are then applied in a similar way to π (pi) terms in dimensional analysis. This method is suitable for use in gas and fluid dynamics.

The method of differential equations is used to draw similarity laws in systems in which the relationships between pertinent variables are known in the form of differential equations. After setting-up the differential equations and boundary conditions of a problem, all quantities are made dimensionless. The collection of the parameters in the dimensionless groups form the similarity laws. This method is also applied to fluid dynamics.

Similarity laws by transformation of variables as defined by Zierep (1971) can be stated as follows: "If there exists differential equations, boundary conditions, and initial conditions for a problem, transformation of the independent and dependent variables are sought in such a way that the number of independent variables are reduced at least by one. Owing to the resulting collection of independent variables, a statement of similitude arises by which systems may be transferred into each other." For two independent variables this leads to ordinary differential equations that can be integrated analytically or numerically.

Yong (1968) studied the possibilities of using these different methods to develop similarity requirements between the model and prototype systems and concluded that the dimensional analysis was the simplest and the most easily applicable technique. Others required extensive knowledge of characteristic equations which are necessary for a complete solution of the problem. The availability of detailed information about these methods and their use in the literature make it unnecessary to discuss them here (Langhaar, 1954 and Zierep, 1971). Dimensional analysis has been accepted as a very useful tool to derive similarity laws in the model study of systems such as soil-machine systems where very little knowledge is available about the inter-relationship of pertinent variables. Barns et al (1960) and Schafer et al (1968) applied the theory of similitude and dimensional analysis to study the effect of different variables on the performance of the discs and developed a disc performance prediction equation. Principles of these techniques have also been applied to predict the draught requirement of chisels, by Reaves et al (1968); Wang and Laing (1970) and Wang et al (1972) plane soil cutting blades, by Wismer and Luth (1972b), cultivator sweeps by Sirohiand Reaves (1969) and mouldboard ploughs by Larson et al (1968); Wang and Lo (1973) and Krastin (1973). Yong (1966 and 1968) gave a general review of these techniques and their possible applications to soil-machine systems. He suggested that most of the models used in these studies were distorted. The reason for this was given by Schafer et al (1969). He quoted from his study to interpret distortion in the similitude of a soil-machine system that: "because of the inability to scale soil properties properly, distorted model theory must be used for soil-machine systems."

Other Techniques

The main example of this category is the work done by Gee-Clough et al (1977e) at the NIAE in which they applied the principles of dimensional analysis suggested by Krastin (1973) to the result obtained from the actual field and machine conditions and utilised curve fitting techniques to determine the coefficients for the prediction equation. Part of this work combined with the soil mechanics theory suggested by Söhne (1960) was used to develop a more comprehensive plough draught prediction equation for the purpose of the current study. Derivation and application of this equation will be discussed in Section 4.2.

3.9 Soil Performance (Compaction)

Performance of the soil during a tillage operation can be evaluated under the following categories:

- effect of the soil on tractor performance;
- effect of the soil on the implement performance;
- soil damage.

The first and second categories have been discussed in detail in sections 3.7.1 and 3.8.1. Greater emphasis is placed in this section on the evaluation of damage which can occur to the soil during the tillage operation due to excessive soil compaction. The structural damage to the soil can be caused either by excessive wheel slip, high tractor load or a combination of both. Wheel slip causes smearing of the soil while high tractor loads cause compaction. As smearing increases at high levels of wheel slip when the tractive efficiency decreases, quantitative evaluation of smearing is accounted for in evaluation of tractive efficiency. No such approach is available to evaluate the effect of soil compaction and this damage usually is evaluated by the assessment of the financial loss through the associated crop yield reduction. This reduction is due to changes of the physical, mechanical and chemical properties of the soil as a result of increased soil density but the interactions between the various factors and their significance in relation to yield loss remains elusive.

Compaction can be studied under the following three categories:

1. factors affecting soil compactability;
2. prediction of soil compaction;
3. effect of soil compaction on the mechanical, physical and chemical properties of the soil, crop growth pattern and yield.

3.9.1 <u>Factors Affecting Soil Compactability</u>

Soane (1970) defined compaction as a process in which the rapid application of a load results in the increase of the soil dry bulk density and the associated decrease of air-filled porosity without change in moisture content. He also studied the factors affecting the soil compactability under two main categories of soil and load characteristics.

The soil variables such as organic matter (Free et al 1947), particle or aggregate size and pore space distributions (Lull, 1959) and moisture content have a marked effect on soil compactability. Foster (1962) found that bulk density was an inverse linear function of the soil moisture content, while Lambe (1962) and Raghavan et al (1976 and 1978a) found that dry bulk density under a constant compacting effort was a parabolic function of the soil moisture content. Other soil properties influencing soil compactability are soil moisture tension and sub-surface drainage (Steinhardt and Trafford, 1974 and Steinhardt, 1976).

Load characteristics affecting soil compaction are summarised by Soane (1970) as: surface pressure, distribution of pressure, impact effects, shape and size of loaded surface, total load, vibrational component, rate and duration of application of stress and the presence of shear stress. Surface pressure and its distribution is highly dependent on the dimensions of the tyre, tyre contact area which itself is dependent on the sinkage, the size of the applied load and dynamic weight transfer. Impact forces and vibrational components are not so important during a tillage operation. The duration of the application of stress and the presence of shear stress strongly depend on the amount of wheel slip. The presence of shear stress at the time of compaction has a pronounced effect on the shape of the bulk density - soil moisture content curves. Figure 3.3 and 3.4 show the effect of shear stress on the changes in the bulk density of sand and sandy loam soils due to changes in the soil moisture content under different levels of pressure (Raghavan and McKyes 1976).

3.9.2 Prediction of Soil Compaction

Despite the importance of the soil compaction on both machine and crop performance, there is little published work on the mathematical or empirical prediction of changes on soil volume under different loads with varying soil and environmental conditions. The change in the bulk density of the soil is the most commonly used measure of soil compaction. Some authors, however, have used other kinds of soil compaction measurements. Dunn and Lyford (1946) used porosity, Swanson and Jacobs (1956) used the resistance to the penetration of a 30° cone (cone index) and Eriksson et al used the new term of the 'degree of compactness' which is the actual bulk

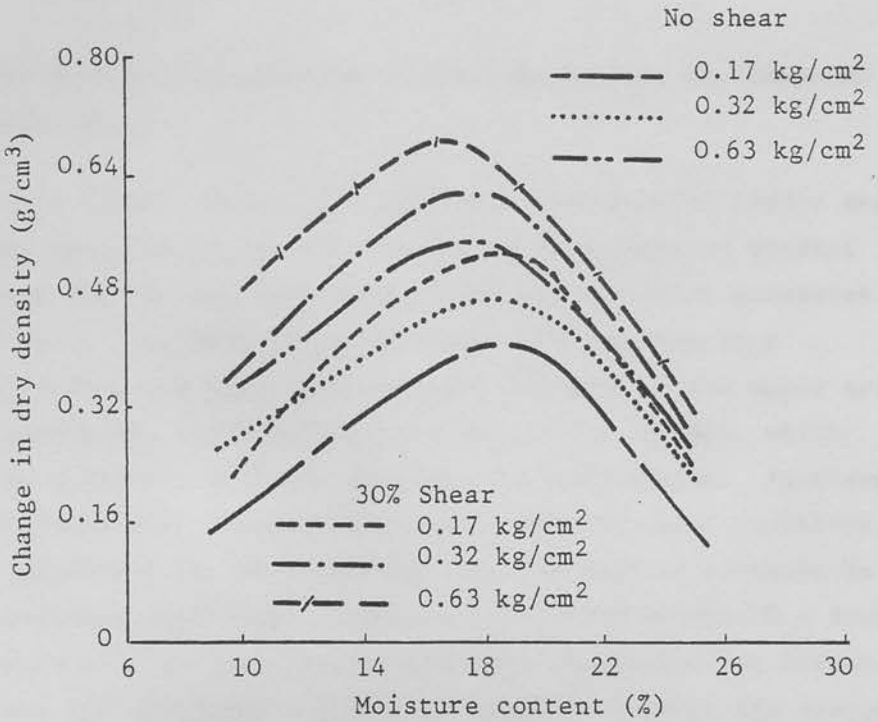

FIG. 3.3: Change in dry density vs. moisture content for tests in a pure shear box with and without shear for sandy soil. (Raghavan and McKyes 1976).

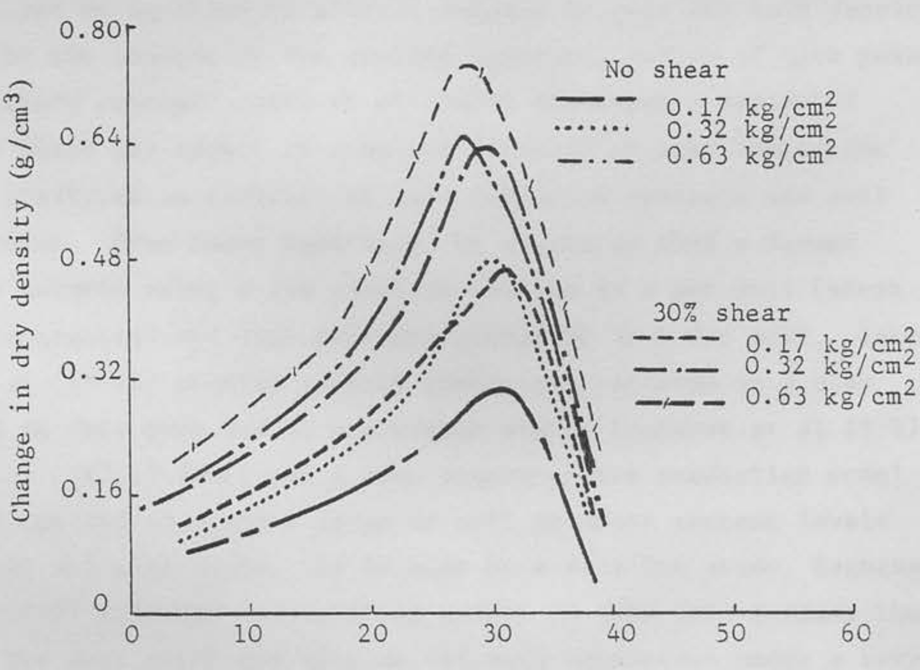

FIG. 3.4: Change in dry density vs. moisture content for tests in a pure shear box with or without shear for sandy loam soil. (Raghaven and McKyes 1976).

density of the soil as a percentage of the bulk density at compacted standard conditions.

Soehne (1958) applied the work done by Froehlich (1934) and the Boussinesq formulae to his own studies in an attempt to predict soil compaction for varying tyre sizes, load and inflation pressures on different soils. He related the pressure distribution to a concentration factor and suggested that the pressure in the upper soil layer is determined by the specific pressure at the surface, which depends on the inflation pressure and the soil deformation. Furthermore, Soehne (1958) found that changes in the soil porosity and, therefore, in the soil compaction can be predicted from the applied pressure by means of logarithmic equations. Fekete et al (1975) undertook a study of the influence of a rolling tyre on the soil compaction for different soil conditions and developed a graphical model to predict the changes in the soil bulk density due to changes in the applied pressure for different levels of tyre sinkage, soil initial bulk density and moisture content. He also suggested some mathematical relationships between pertinent variables. In a comprehensive study to relate soil dry bulk density to applied pressure and soil moisure content, Raghavan et al (1976) developed an equation to predict changes in soil dry bulk density in relation to the changes in the applied pressure, number of tyre passes and soil moisture content. Amir et al (1976) developed a series of equations by which the effect of time and drainage on soil compaction can also be predicted in addition to tyre inflation pressure and soil moisture content. From these equations, he suggested that a farmer could decide between using a low pressure machine in a wet soil (short time after saturation) and high pressure mechanism in a dry soil. Later Raghavan et al (1977a) studied vehicle compaction patterns in a clay soil. Based on this work and on a previous study (Raghavan et al 1976), Raghavan et al (1977b) developed a more comprehensive prediction model which can be applied to a wider range of soil moisture content levels for both sandy and clay soils. In an even more detailed study, Raghavan and McKyes (1978) extended the existing models to take into account the position of the data point and slip on the soil compaction under a tyre. This study was carried out for sand, sandy loam, loamy sand and clay soils. Although variations on the soil compaction can be predicted up to a certain level of accuracy by these models, they require extensive laboratory and in situ measurements and produce cumbersome results. Even accepting the inadequacies of the existing compaction theories, evaluating the quantitative effect of compaction on the yield of different crops present further difficulties.

3.9.3 Effect of Soil Compaction on Crop Growth Pattern and Yield due to its Effect on the Physical, Mechanical and Chemical Properties of the Soil

Despite the extensive studies undertaken by many researchers to evaluate the quantitative effect of soil compaction on crop growth pattern and yield, no reliable procedure exists by means of which quantitative response of crops due to changes on soil bulk density can be predicted. Contradictory results from different observations indicate the complexity of the problem. In some cases, a major increase of the crop yield and a noticeable improvement in the crop performance have been reported. Heath (1937) found that maturation of field-grown cotton plants was hastened by compaction. He also reported that the total dry weight, dry weight of buds and flowers, height, number of green leaves, number of green bolls and open bolls were all superior on the compacted soil. Another example of improved crop behaviour due to increased soil compaction is shown by Flocker et al (1959a). They stated that improved germinations and higher levels of protein and anthocyanin was recorded on the tomatoes grown on compacted soils than on the ones grown on uncompacted soil. Earlier wheat crop emergence on the compacted plots has also been reported by Feldman and Domier (1970).

Although very rare, increased crop yield due to increased soil compaction up to a certain limit has been observed by a few researchers. Hubbel and Staten (1951) stated that cotton yields were higher on the plots with moderate and severe compaction when compared with uncompacted and slightly compacted plots. Flocker et al (1960) obtained similar results for tomatoes grown on soil ranging from sandy to clay loam with bulk densities less than 1.3 g/cm^3. Rosenberg and Willits (1962) found an increase of 50% in the yield of barley when soil bulk density was increased to an even higher degree of 1.6 g/cm^3.

Contrary to the conclusions of the foregoing studies, the results obtained from the majority of the experiments conducted elsewhere have shown that the compaction has a consistent retarding effect on both crop behaviour and yield. The diverse effects of increased compaction on the behaviour of field crops was first reported by Taubenhous et al (1931). He quoted that, "enlarged clavate bases of stem indicated that trans-:location had been impeded by pressure of the soil on the plant." This was noticed on cotton. In another study on the effect of soil compaction on cotton behaviour, Heath (1937) observed delayed silking and tesselling dates due to soil compaction. On tomato plots, compaction decreased budding (Flocker et al 1959a : Flocker and Menary, 1960) and fresh weight (Flocker et al 1960). On corn plots, germination, maturity (Adams et al 1960), tesselling and silking dates were delayed and stands were reduced (Phillips and Kirkham, 1962). Raghavan et al (1978b) quantified crop behaviour by relating plant height and number of plant leaves to the product of the number of tractor type passes and contact pressure (compaction factor), time of treatment and number of days after seeding. In all the equations reported, plant height and number of leaves were diversely corrolated with the compaction factor.

The effect of increasing compaction on the yield of different crops have also been examined. Bavere and Farnsworth (1940), Smith and Cook (1946) and Blake et al (1960) noted a considerable reduction in the yield of sugar beet due to decreased soil porosity. Yield of potatoes (Bushnell, 1953; Flocker et al, 1960; Adams et al, 1961), cotton (Saveson et al, 1958), tomatoes and certain winter crops have also been decreased due to soil compaction (Flocker et al, 1958a, 1959a and 1959b; Flocker and Menary, 1960). Dramatic decrease in the yield of corn due to soil compaction has been reported by Swanson and Jacobson (1956), Adams et al (1960) and Phillips and Kirkham (1962). Results of the experiments undertaken by Rosenberg and Willits (1962) showed a similar effect for barley. From the preceding review of the literature and the conclusions reached by some researchers, it is fair to suggest that the effect of compaction on crop yield and behaviour is parabolic. That is, crop yield is increased by increase on soil bulk density up to an optimum point above which any increase on bulk density will result a drop on the crop yield. Flocker et al (1959b), Rosenberg and Willits (1962), Rosenberg (1964), Soane (1970), Hakansson (1973), Erikson et al (1974) and Raghavan et al (1978b) all agree on the fact that there is a parabolic relationship between crop yield and soil compaction, but so far the final form of the equation which can be applicable universally to the varying crops, soils and environmental conditions, have not been established. The effect of soil compaction on the yield and growth pattern of different crops can be attributed to its effect on the mechanical, physical and chemical properties of the soil. Excessive compaction increases soil shear strength and resistance to penetration of cones and plates into the soil. Soil physical properties such as moisture content, aeration, bulk density, temperature and hydraulic conductivity are also effected by compaction (Rosenberg, 1964 and Douglas and McKyes, 1978). Soil compaction has an indirect influence on the chemical properties of the soil such as oxygen diffusion, manganese availability and nitrification. (Passioura and Leeper, 1963).

Despite the important effects of these factors on a machinery selection programme, lack of mathematical relationships for the prediction of both compaction and its effect on the crop yield made the exclusion of this part from the current study inevitable. Nevertheless, the programme can be improved to take into account this factor when reliable prediction equations become available.

3.10 Matching the Tractor and Implement

The correct match of the tractor-implement-soil combinations forms the most important and decisive part of a tractor selection programme for tillage operations. The improper choice of any of the three components of the tillage system which are, the tractor, the implement and the soil or any other factors affecting these can cause substantial drop on the output of the system and may even immobilise the operation. The tillage operation is halted when the draught required by the implement and the rolling resistance of the tractor exceeds the net pull produced by the tractor. Factors contributing to the immobilisation of the tillage system are either an increase in the draught requirement of the implement and rolling resistance of the tractor, or a decrease in the tractive efficiency and traction of the tractor which in itself results in the decrease of the amount of the net pull produced by the tractor (Table 3.1).

TABLE 3.1 Constraints causing immobility of the tillage system

Tractor Constraint	weight is too small; power is too low; drive wheel tyres are too small; tyre inflation pressure is too high.
Implement Constraints	width is too large; working depth is too great; angles of approach of the implement are too large.
Soil and Topographic Constraints	soil is too wet; soil is too dry; soil surface is too slippery; gradient is too steep; operating speed is too high.

In sections 3.7.1 and 3.8.1 the main factors affecting the pull/draught pattern of a tillage system have been identified and discussed in detail. Tractor immobility is not always the only reason for the discontinuation of a tillage operation. Even where the tractor can be operated, there are other occasions when the tillage operation cannot proceed, for example:-

- the tractor is too small, work rate is too low and completion of the operations is not possible in the time available so that labour costs and timeliness penalties are high;
- the tractor is too heavy, soil compaction is too high and crop loss due to compaction is inevitable;
- tractor is too large and under-utilised, the capital cost is too high, timeliness penalty and labour costs are low but soil damage and operating costs are high;
- tractor drive wheels are too large and unsuitable for the tractor design;
- width of the implement is too small, the work rate is low, insufficient working days are

available and timeliness penalties and labour costs are high;

- working depth of the implement is too shallow and cultivation unacceptable;
- angle of approach is too small and ploughing is too shallow;
- soil is too wet and smearing and permanent soil damage occurs through excessive slip and compaction, labour costs and timeliness penalties are low, fuel cost is high and efficiency is too low;
- soil is too dry, clods occur, heavy draught forces are incurred and while soil damage is low due to less compaction, timeliness penalties are high, fuel cost is high and efficiency is too low;
- operating speed is low, work rate is low, timeliness, labour and fuel costs are high and there is little time to complete the operation.

An efficient tractor selection programme should balance these factors and come up with a system in which the smallest tractor pulling the largest possible implement with the highest possible work rate (speed) has the least soil damage least draught requirement, a desirable depth, least timeliness, labour, fuel, capital and maintenance costs, optimum slip and maximum tractive efficiency. To obtain such a system, a knowledge of the restrictions and the limitations of these elements is essential.

Although the choice of a small tractor in a good year for a small farm can prove to be the right decision, in a bad year for larger farms, it is disastrous. If a small tractor is purchased instead of a large one, the power output is lower and, therefore, a smaller implement should be utilised. This results in a considerable reduction on the implement width and speed which directly affects the work rate of the system, the time required for the completion of the job and delays the availability of the land for the subsequent seeding operation. The economic evaluation of late drilling has been studied by many researchers such as Zuber and Constien (1968) and Hunt and Patterson (1968). A detailed study of this phenomenon will be carried out in section 3.11.3 Another disadvantage of a prolonged tillage operation is the inflation of labour and fuel costs as these are linear functions of the time. On the other hand, the choice of a small tractor requires a lower investment and involves less risk of being idle in a good year (dry year).

Tractor weight can be increased up to a certain level to obtain increased traction and its magnitude is highly dependent on the dimensions of the tyres used on the drive wheels of the tractor. Equation 3.2 indicates the relationship between the load carrying capacity and tyre dimensions of a drive wheel on a tractor as suggested by Komandi (1976). Dwyer and Pearson (1976) found that the tractor power also is a restricting factor for the load carrying capacity of the tyre in order to obtain maximum tractive efficiency. They concluded that mass/power ratio was inversely related to the travel speed and this relationship was later presented graphically (Dwyer, 1978) (Figure 3.5). Baily and Burt (1976) had demonstrated this relationship in the form of a three dimensional surface (Figure 3.6) and used regression analysis to fit the best equation to these data:

$$\frac{Q\omega}{W} = a_1\, TR + a_2.TR^2 + a_3.TR^3 + a_4 \qquad 3.11$$

where:

a_i = regression coefficients

Q = input torque

TR = travel reduction

W = dynamic load

ω = angular velocity

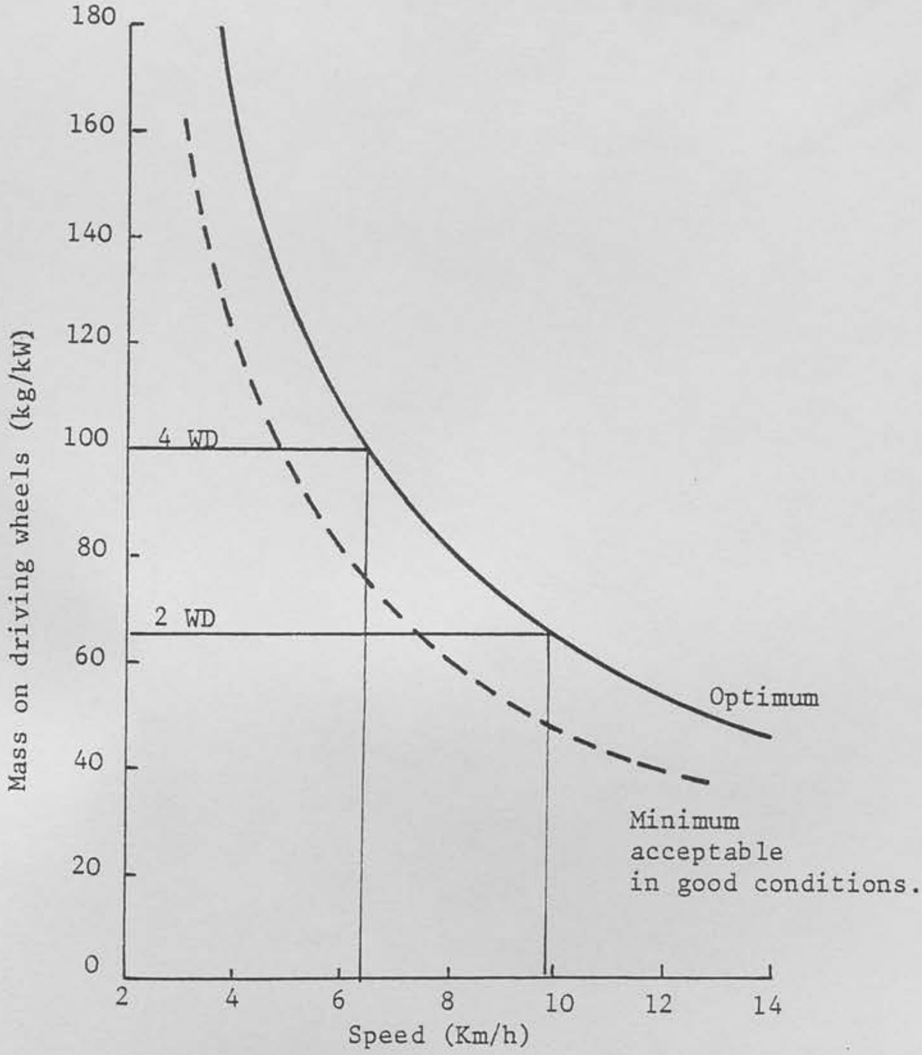

FIG 3.5: Mass on driving wheels required for maxium tractive efficiency at different speeds. (Dwyer 1978)

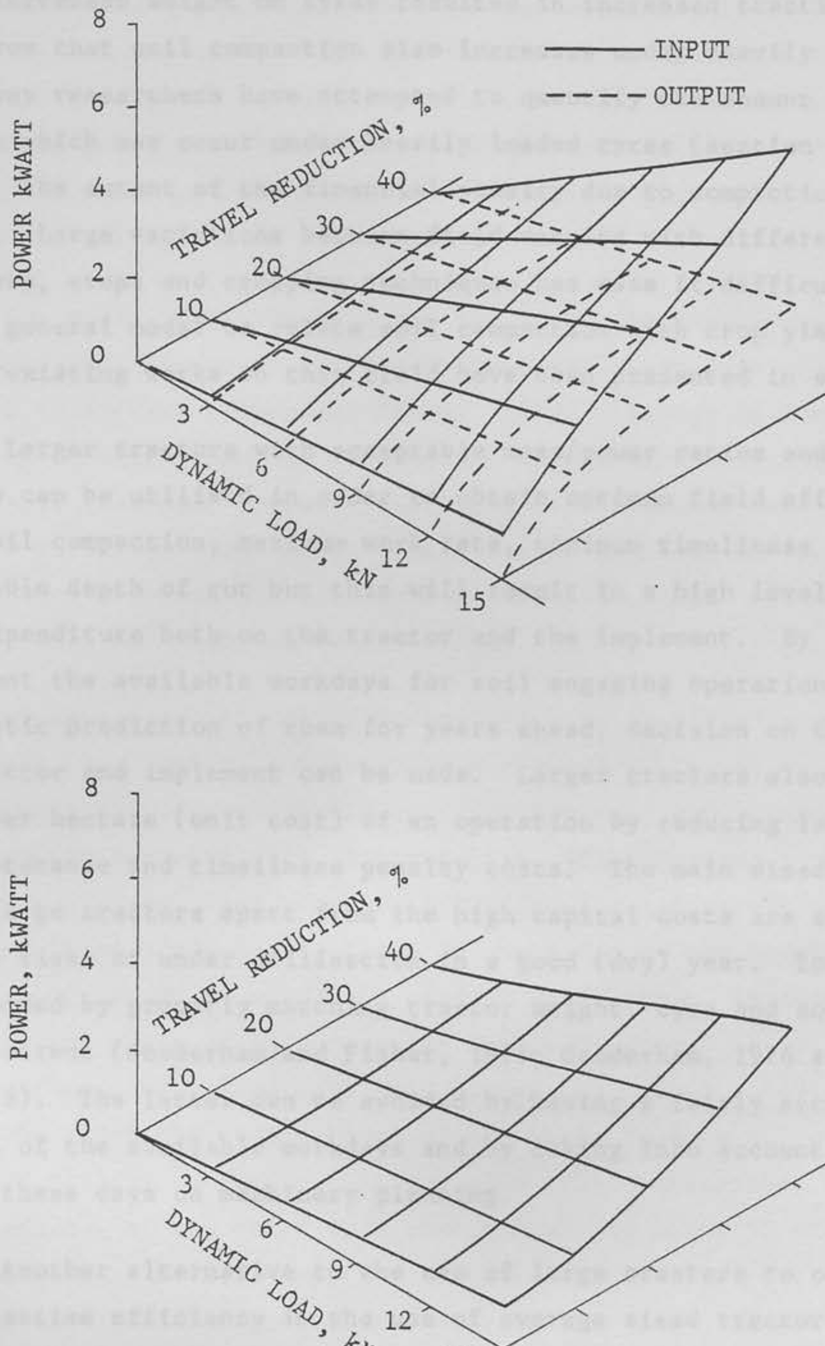

FIG. 3-6: Input power, output power, and power losses surfaces for 12.4-28 tire on soft-base conditions. Mean velocity = 0.299 m/s, standard deviation = 0.009 m/s. (NTML Photo Nos. P-10, 275a,b).

After: Baily and Burt (1976).

Painter (1980) used tyre deflection under a load as a variable limiting the load carrying capacity of a tyre. Although it is generally accepted that the increased weight on tyres resulted in increased traction, it is equally true that soil compaction also increases under heavily loaded tyres. Many researchers have attempted to quantify the amount of compaction which may occur under heavily loaded tyres (section 3.9) and therefore, the extent of the financial penalty due to compaction induced crop loss. Large variations between field results with different types of machinery, crops and cropping techniques has made it difficult to develop a general model to relate soil compaction with crop yield. A review of existing works on this field have been presented in section 3.9.

Larger tractors with acceptable mass/power ratios and optimum tyre sizes can be utilised in order to obtain optimum field efficiency, minimum soil compaction, maximum work rate, minimum timeliness penalty and desirable depth of cut but this will result in a high level of capital expenditure both on the tractor and the implement. By taking into account the available workdays for soil engaging operations and probabilistic prediction of them for years ahead, decision on the size of the tractor and implement can be made. Larger tractors also retard the cost per hectare (unit cost) of an operation by reducing labour, fuel, maintenance and timeliness penalty costs. The main disadvantages of using large tractors apart from the high capital costs are soil damage and risks of under utilisation in a good (dry) year. The former can be avoided by properly matching tractor weight, tyre and soil moisture content (Gooderham and Fisher, 1975; Gooderham, 1976 and Dwyer, 1978). The latter can be avoided by having a fairly accurate prediction of the available workdays and by taking into account the effect of these days on machinery planning.

Another alternative to the use of large tractors to obtain maximum tractive efficiency is the use of average sized tractors with larger tyre dimensions or the use of small tyres with higher inflation pressure to maintain optimum mass/power ratio. Dwyer (1978) suggested that most of the two wheel drive tractors used in the U.K. are under-tyred. The use of large tyres on small tractors can be impractical and high inflation pressure in small tyres can cause extensive soil damage due to soil compaction (section 3.9), working width and depth can also be reduced to enable a tractor to produce enough drawbar pull to offset the resistance of the implement. The former will result in a substantial drop on the work rate of the implement, therefore, increased labour, fuel and timeliness penalty costs. The latter can reduce the quality of the work and, therefore, can result in a loss of yield and quality of the crop which is to be grown in that particular land.

The angle of approach of the implement can also be reduced in order to decrease the amount of draught required, therefore enabling the tractor to operate (Payne and Tanner, 1959). Ploughing when the soil is wet, although reducing the draught requirement of the implement, also decreases traction, travel speed, tractive efficiency and work rate due to excessive slip. Soil damage due to smearing and permanent soil compaction increase drastically with wet ploughing. (Gooderham and Fisher, 1975 and Raghavan et al, 1978a).

In some cases ploughing a very dry soil is either preferable or inevitable (in tropical countries or dry years). It may be favoured by some farmers in order to obtain improved traction and reduced soil compaction which may result in high tractive efficiency and less soil damage and, therefore, less crop loss, but it also may result in formation of large clods and increase in costs due to the requirement for an extra operation to eliminate clods. In addition, because energy requirements and costs of the operation inversely depend on soil moisture content (Woorhees and Walker, 1977 and Witney and Oskoui, 1979) dry ploughing can alter the cost pattern of the whole farm by increasing unit cost of tillage operation. It can also have considerable influence on the scheduling of the other farm operations. In order to obtain enough days with a low soil moisture content in temperate climates, the ploughing operations can suffer a considerable delay which consequently will delay seeding and harvesting operations and cause a very high timeliness penalty and disarray in the overall farm programme.

Low speed ploughing can also be regarded as a technique to reduce the draught requirements of the plough and improve traction.

The type and extent of the effect of speed on both the draught requirement of the plough and traction and tractive efficiency of the tractor has been fully discussed in sections 3.7.1 and 3.8.1. Low speed ploughing may be inevitable in extremely wet or dry lands and/or when the tractor is pulling a heavy plough. In general, however, high speed ploughing increases the work rate of the plough and reduces the unit cost of the operation by reducing costs of fuel, labour and timeliness penalty.

The ploughing speed limitation can be achieved by balancing the other pertinent variables in the plough draught and tractor traction prediction equations (sections 3.7.2 and 3.8.2) and the optimum speed level can be chosen for a given soil and operating condition.

Matching the tractor/implement/soil system can also be done quantitatively using minimum cost or maximum profit criteria. Hunt (1963, 1966) used algebraic minimisation procedure to obtain the width of the implement for which the costs are a minimum. Hunt (1971a) described a similar procedure for determining the economic power level for big tractors using large implements. Scarborough and Hunt (1973) modified these programmes to include a logarithm for determining the optimum replacement period for the equipment, draught calculation for implements and scheduling operations with a competitive nature.

MacHardy (1965 and 1966a) described a method based also on cost minimisation and used Lagrange Multipliers to determine implement productivities and tractor horsepower such that the annual fixed machinery cost is a minimum. Later, he suggested that the machine size can be determined by minimising the sum of the fixed annual cost and timeliness penalties. Another machinery system matching procedure which was based on cost minimisation was described by Burrows and Siemens (1974) in which the costs of machinery, labour and timeliness were minimised in relation to the machinery combination and size. Hughes and Holtman (1979) matched the machinery system for the time available and, therefore, the timeliness costs were not explicitly identified. Drawbar power requirements for implements were considered to be constant.

Profit maximising procedures have also been used as a technique to match a machinery system. Frisby and Bockhop (1968) developed a procedure for calculating the area yielding maximum profit for a given set of machinery. They used an analytical procedure suggested earlier by Link and Bockhop (1964) to match a machinery system to a set of farm job requirements and evaluate the match for the timeliness of the operation. Zoz (1974) matched tractor and implement on the basis of the implement draught requirement and tractor pull capability. He optimised the travel speed with respect to the power constraint and productivity and produced a graphical procedure based on his previous works (Zoz, 1972 and 1973). Woorhees and Walker (1977) adopted a similar procedure to model the tractor implement combination. They also included the effect of soil moisture content in order to define soil tractionability. Bowers (1975) used a different procedure to match the tractor/implement system. He assumed a particular size of tractor and matched proper implements for that tractor using average implement draught requirements. Singh and Holtman (1977), in a rather comprehensive study, assumed a power level and calculated the productivity of the operation subject to constraints on available power, implement size, speed and available time at a given probability level. He used the average draught requirement which did not take into account the variations on soil moisture content. Gee-Clough et al (1977e and 1978) developed a procedure based on Zoz's (1974) work but suggested that the tractive efficiency should also be used as a constraint in matching tractors to implement. They calculated drawbar power produced by the tractor and the draught requirements of the plough by using empirical equations developed by Dwyer et al (1974b) and Krastin (1973). An improved version of this method was utilised in current study.

3.11 Cost of the Tillage System

While profit maximisation or cost minimisation are not the only management criteria for an evaluation of an enterprise, identifications of the different cost items is essential to the economic appraisal of any system and a machinery system is no exception. Two groups of costs can be identified in a machine system, namely:

i) cost of machinery;

ii) cost of lost time (timeliness penalties).

3.11.1 Cost of Machinery

These costs are directly associated with the machinery system and are usually separated into fixed and variable costs. Chancellor (1968) further subdivided the variable costs into energy costs and time costs. He used the conventional definition for fixed costs (Hunt, 1956) but included that portion of the depreciation which is associated with obsolescence and defined the energy costs as those costs which are in direct proportion to the amount of work done by the machine regardless of the size. The energy costs included fuel, lubrication, maintenance and repairs and the proportion of the depreciation which is associated with the wearing out of the machine due to use. Time costs are defined as those costs directly related to the hours of tractor operation. The main item in this category is the operator's wages. As the amount of work done by the machine is directly related to the hours of use, therefore, segregation of the last two categories is not really necessary. In this study, the usual classification under two groups of fixed and variable costs will be used.

Fixed Costs

Fixed costs are those items of agricultural machinery expenditure which do not change through variation in the amount of use of machinery. Identification and prediction of these costs are easier than variable costs. The following items are normally regarded as fixed costs in machinery cost analysis:

initial capital;	insurance;
taxation;	sheltering;
inflation;	interest on investment.

Initial capital is the amount of cash or credit required when purchasing a machine and is usually funded by the cash available from the farm income, investment capital and/or a bank loan.

The capital investment is proportional to the size of the machine. The purchase prices of tractors are linear functions of their engine power (Hunt, 1963 and MacHardy, 1965). The analysis of prices of tractors for the year 1975 by Cottrell and Audsley (1976) also confirmed this theory. They separately identified the price of added ballast in the general form of the tractor price equation:

$$TPP = C_1 \times POWER \pm C_2 \times BALL + C_3 \qquad 3.12$$

when:

C_1, C_2 and C_3 = coefficients depending on the currency and units used;

BALL = the weight of added ballast in addition to tractor weight;

POWER = tractor engine power;

TPP = tractor purchase price.

For 1975 British data, Cotterell and Audsley (1976) found the following equation:

$$TPP = 48.15 \times POWER + 253.6 \times BALL + 1246 \qquad 3.13$$

where BALL is in tonnes, POWER in kW and TPP in pounds sterling. An equation similar to equation 3.12 was found for the 1980 British data by the author. Although the coefficients of the equations can vary from one year to another and from one country to another, the availability of up-to-date data from most of the manufacturers for different years and countries justifies its use.

The same theory can be applied for the price of the implements used. The purchase prices of ploughs were correlated with the width of the ploughs and the square root of the ploughing speed. The prices of chisel ploughs were also correlated with widths and speeds but a quadratic function of width gave the best agreement. The purchase prices of rotary diggers were found to correlate with a cubic term of their power input and a linear term of their width (Cottrell and Audsley, 1976).

Other items of fixed costs, such as insurance, taxation interest on borrowed capital and effect of the inflation are direct functions of the size of the machinery and indirect functions of management policies. These costs can easily be predicted with a consistently high level of accuracy and accounted for in the machinery cost calculations. Audsley and Wheeler (1978) included these items in the calculation of the present annual cost of farm machinery. Sheltering is the only item of machinery fixed costs for which quantitative evaluations and economic justification is not yet clarified. Hunt (1956) stated that sheltering can improve the expected useful life of machinery and has a constant retarding effect on the average annual estimated repair expenses. He suggested that the annual cost of a typical shed could amount to 1% of the original purchase price of the machine. The use of cheap shelters, such as empty grain stores, driveways or unused animal sheds can reduce the annual cost of sheltering to as low as 0.5% of the machine purchase price. This cost is not usually accounted for in machinery cost calculations and selection programmes and is assumed to be constant.

Variable Costs

Variable costs are more difficult to identify and evaluate than fixed costs. The term 'availability cost' has also been used to identify this group of farm machinery costs (Kolarik et al, 1979). Various definitions have been proposed by different authors. Hunt (1956) defined the variable cost of a farm machinery system as "those costs which increase proportionally with the amount of operational use given by the machine." He categorised the cost of fuel, lubrication, daily servicing and maintenance, power and labour (operator) as dependent on the use of the machine and the two other cost items, depreciation and cost of repairs, as functions of both use and the calendar-year time. Kolarik, et al, (1979) used a similar definition for availability costs. They quoted: "availability costs are those costs directly associated with the availability of a system." They used a similar classification to Hunt (1956) but excluded the depreciation and added repairs and timeliness costs to their list of variable costs. In this study, the variable cost of a tillage system will be reviewed under the following categories:

depreciation;	labour cost;
fuel costs;	maintenance costs;
repair costs.	

Depreciation

Depreciation, often the largest cost of a farm machinery system, is the reduction in value of the machine through the usage of the machine and the passage of time. It can be calculated from the value of the machine at the beginning and end of a given year, but, for the machinery selection programme, where the machine is not yet purchased it is necessary to develop a method of predicting the estimated value of the machine at the end of a given year. Hunt (1956) summarised the methods available in the USA for the evaluation of the depreciation of agricultural machinery.

The straight line method is the simplest approach. Annual depreciation is calculated by simply deducting the salvage value of the machine from the actual purchase price and dividing by the number of years the machine is owned. The depreciation rate calculated by this method is constant for every year.

In the declining balance method, the depreciation is the difference between the remaining value of the machine at the beginning of the year in question and the previous year. The depreciation is different for each year in the life of the machine.

Using the sum of the years-digit method, the depreciation for a given year is calculated by adding the digits of estimated machine life, dividing the results into the number of years of life remaining for the machine and multiplying that by the difference between purchase price and salvage value.

The sinking fund method, according to Hunt (1956), considers the problem of depreciation as one of establishing a fund which will draw compound interest. Uniform annual payments to this fund are of such a size that by the end of the life of the machine, the fund and their interest, have accumulated to an amount which will purchase another equivalent machine. He recommended that this method approximates to the actual depreciation of the equipment with slow and fast depreciation rate for the early and final years of the machine life, respectively. This method has been adopted by Audsley and Wheeler (1978) in the development of a machinery costing programme which was utilised in current study.

Labour Costs

Labour costs or machine operator costs of a tillage machinery system are directly proportional to the hours of utilisation of the machinery and current tax and insurance rate. The amount of operator cost allocated to tillage operation can be calculated on an hourly basis or as a percentage fraction of the operator's yearly salary depending on the number of hours devoted to the tillage operations.

Fuel Costs

Fuel costs are strongly dependent on the size and variation of tractor power as well as being a function of hours of utilisation. The types of fuel used has also an influence on the cost of fuel required to complete a given task. Pfundstien (1960) in a study to compare the effect of varying fuel type on the overall cost of tractors developed a set of summary tables by means of which costs of three tractors using gasoline, liquid petroleum gas and diesel can be compared. Cost factors affected by fuel type were, tractor size and price, depreciation, interest, taxes, insurance, fuel, lubrication, service and maintenance, hours of use and amortisation time. The effect of varying power on the tractor fuel economy has also been studied. Sulek and Lane (1968a) analysed Nebraska test data and found linear relationships between tractor fuel comsumption operating at the maximum p.t.o. power and part-throttle for three different fuel types and concluded that the maximum p.t.o. power fuel economy of a tractor is a good indicator of its part-throttle fuel economy in most cases. Average values of fuel costs have been usually used in most of the machinery cost analysis models. In another study, Sulek and Lane (1968b) established unbiased part-throttle fuel economy characteristics for three different fuel types. They found that the mean fuel economy of a fuel class is a poor estimator of an individual tractor model. Cottrell and Audsley (1976) calculated tractor fuel costs per unit work done (hectare) from the tractor maximum p.t.o. power and work rate using a tractor fuel energy content factor. This procedure was modified to incorporate the effect of part-throttle fuel consumption and used in the current study.

Service and Maintenance Costs

Maintenance costs are those cost items of machinery associated with the maintenance carried out during machine ownership. As defined by Boyd and Dickey (1949) and quoted by Puzey and Hunt (1966): "maintenance keeps an asset in an operating condition and helps to maintain its efficiency or that of the workers who use it. Such expenditure includes cleaning, oiling, greasing, painting and similar items."

Maintenance costs are usually regarded as part of the combined 'repair and maintenance' costs and seldom calculated separately. Liang and Link (1970) used the term 'preventive maintenance costs' which in nature is more a repair cost than a maintenance cost and defined it as those costs associated with the repair and replacement of those elements of the machine which are likely to break down in the very near future. This is a useful practice if the probability of the breakdown of an element in the middle of a very busy season is too high. Maintenance costs are calculated by accumulating the amount of cost required to complete an estimated number of maintenance jobs. The number and nature of these jobs are usually obtainable from the manufacturers' instruction manuals. Tractor maintenance items have been identified and fully studied on sixty tractors by Webber (1958). This cost is insignificant when compared with other machinery cost items and can be neglected (Hunt and Fujii, 1976).

Repair Costs

Repair cost, the most important and the most difficult cost to assess and predict, is that part of machine variable costs which is associated with the unplanned replacement, amendment or adjustment of parts of a machine which will bring the system back into operation. Boyd and Dickey (1949) as quoted by Puzey and Hunt (1966) stated that: repairs are those normally required to keep an asset in an efficient operating condition. Repair costs may be considered as being composed of two parts. The first is the cost of a repair including the cost of labour and parts and the second is the cost of delay in the field operation due to machine 'down time' while repairs are made (Batterham et al, 1973). In this section, emphasis will be placed on the actual cost of the repairs and the second part (down time cost) will be examined in the following section.

Repair costs are affected by initial cost, type and quality of the machine, number of hours of annual use, age of the machine, proficiency of the operator, use inspections, maintenance and service frequency, type of terrain, type of crop and crop yield.

Despite the complexity of the problem, the mathematical prediction of repair costs and the probabilistic prediction of the frequency of occurrence of a breakdown have been approached by many researchers. Puzey and Hunt (1966), in a study of the data made available by farmers interviews, Illinois Farm Bureau Farm Management Service and data used by Mueller and Wilken (1963) examined the possibility of developing repair cost patterns for key components of farm machinery. They hypothesised that the restoratinn expenses of machinery components are due to four causes of random events, management,failures, transportation and accumulated wear and suggested that the repair costs pattern of a component due to accumulated wear in a static operational environment as related to accumulate use should have the appearance of a stairway with identical steps at the origin. Chancellor (1968), from the examination of data for California, Malaya and East Africa, concluded that the repair costs of farm machinery are a function of their new price, engine power and hours of use. Laing and Link (1970) used the seven standard equations (developed by Larson and Bowers (1965)and reported in the Agricultural Engineers' Yearbook) to develop a preventive maintenance scheduling programme. The general form of the equation is:

$$y = a_1 x^{b_1} \qquad 3.14$$

where: $a_1 > 0$ is a constant;

$b_1 > 1$ is a constant;

x is total accumulated hours, % of lifetime hours;

y is accumulated repairs, % of list price.

Bowers and Hunt (1970) analysed the data obtained from a survey of 1600 Illinois and Indiana farms in order to develop mathematical relationships between farm machinery repair costs and pertinent variables. They used a computer programme to produce least square regressions for linear, quadratic and cubic equations to express repair rate functions. The correlations were sought between the total accumulated repair costs, per cent of life of the machine at the point for which the costs are calculated, initial list price of machine and other pertinent variables for several different types of farm machinery. The best fit equations were linear for discs, quadratic for tractors and cubic for the rest of the farm machinery. Correlations were significant but as the coefficients were affected by climate, soil type, operating conditions and quality of operator, the world wide application of these equations is questionable. Equations, similar to equation 3.14 also were fitted to Kansas Survey data by Fairbanks et al, (1971) and good correlations were obtained. Information on farm machinery repair cost patterns for the U.K. is very limited and collection and analysis of data in this field has received very little attention. Gill (1971) examined the data collected for 92 tractors, 57 self-propelled combines and 51 pto type balers from 81 farmers in Hampshire, Berkshire, Oxfordshire and Buckinghamshire for the period 1964-68. Correlations were sought between age of the machine year's work, accumulated work, accumulated repair costs and previous year's repair costs for tractors, combines and balers. For the tractors, accumulated work was responsible for most of the variations (16%) in the annual repair cost. For combines, the variable 'previous year's repairs' accounted for the most of the variations (36%) in the repair costs and for balers, as for the tractors, the single variable responsible for the variation in the annual repair costs was 'accumulated work.' The best fit equations were generally of the form:

$$\ln(y) = a_2 \ln x + b_2 \qquad 3.15$$

where: a_2, x and y are as previously defined and b_2 is a constant.

Other variables examined were work load, soil type, housing, maintenance, crops and weather but no quantitative relationships were obtained. In a recent study, Hunt and Fujii (1976) analysed the eight years data collected from 45 Illinois farms which included 740 tractors and implements. They reported the results in two percentages to evaluate the magnitude of the repair costs and frequency of their occurrence. The first percentage was based on the average annual repair and maintenance costs and the second percentage was based on the number of failures. They provided useful information on the cost and frequency of machinery breakdowns but were unable to suggest quantitative prediction equations.

Attempts have also been made to predict the frequency of the occurrence of failure in a particular component. Hunt (1971b) examined the data collected from 1563 Indiana and Illinois soyabean farmers in order to obtain a criterion for the prediction of the reliability of tractors and combines decreased with accumulated use and the age of the machine and concluded that an average farmer in this area has a 50-50 chance of getting through the season without having a breakdown. This chance is even lower for complex harvesting machinery (25-75%). Despite the existence of the slight correlation betwen breakdown frequency and accumulated use and the age of the machinery, he suggested that the breakdowns are highly random in nature. The quality control practices of manufacturers and the management skills of the farmer also influenced the probability of occurrence of a breakdown incident. Another study of this phenomenon was carried out in Central Illinois by Hunt and Fujii (1976) in order to predict a farm workshop inventory. From the foregoing review of the literature it is evident that there is no complete solution for the prediction of repair costs. The use of standard procedures suggested by ASAE (ASAE, Agricultural Engineers' Yearbook, 1980) are therefore the best available but inevitably introduce errors through applying data collected in one area to a completely different environment. These procedures which were adopted by the NIAE were also utilised in this study (Audsley and Wheeler, 1978).

3.11.2 Factors Affecting Lost Time

Untimely completion of work or unfinished agricultural operations can cause a substantial amount of quantitative and qualitative loss to farm crops which will in turn affect profit. Two major groups of factors usually contribute to the lost time in a farm operation. Firstly, there are factors associated with changes in the weather during the working season such as heavy rainfall, snow, sleet, strong winds and severe draught.

These factors and their effects will be discussed in section 3.12. Secondly, there are factors associated with labour and machine availability, reliability and management such as: breakdowns, servicing, transport, queuing, turning and size and efficiency of machinery.

Breakdowns are the second most important source of lost time after the weather variables and are equally unpredictable. The prediction of time lost during the farm operations due to unexpected breakdowns has received very little attention partly because of the intractability of the problem and partly because of the scarcity of available data. Hunt (1971b) studied the data collected from 1563 farms in Illinois in order to develop a method of predicting farm machinery reliability and concluded that the amount of lost time due to breakdowns was highly variable. Virdin et al, (1979) developed a computer programme to analyse the data on down time available for wheeled-skidders in Central Louisiana. In this study, the emphasis was placed on the identification of the factors creating machine 'down time' and their importance in relation to each other. Parsons et al, (1979) studied the effect of machine 'down time' on the cost pattern of a machinery system. Neither of these studies, however, culminated in a reliable procedure by means of which the amount of time lost due to incidence of unexpected breakdowns and, therefore, its effect on the machinery cost of the time can be predicted. Liang and Link (1970) suggested that the preventive maintenance and repair can reduce the frequency of incidence of breakdown and therefore reduce the amount of time lost in a very busy season. These repairs can be carried out in off-peak seasons when the time is not so critical.

Servicing also can create machine 'down time' but its occurrence is known beforehand and it can be planned in a way that will cause the least possible interruption in the farm operation in a very busy season. Services can be carried out at night or when the machine is unoperational due to other factors such as bad weather.

Transportation of farm machinery from one field to another can also create considerable time lost if the fields are remote from each other. This factor is very important for machinery owned by contractors or by co-operative groups. By effective management and scheduling programmes, this factor can be minimised and accounted for in machinery planning and cost estimations.

Turning and queuing also generate lost time but again can be minimised by effective management and scheduling programmes.

Inadequate capacity or inefficient operation of machines can cause a drastic prolongation in the farm operations and undesirable delays on critical operations which result in a substantial financial loss for the farmer. An undersized power and machinery system results in overloading or overworking, both of which increase the possibility of breakdown (Hunt, 1971b). Inefficient operation of machinery reduces the rate of work and directly affects the time required for the completion of the farm operations. Correctly matching the power/machine systems and the machine/farm systems can eliminate or minimise the effect of these factors on the lost time during farm operations.

3.11.3 Effect of Date of Sowing on Grain Yield of Spring and Winter Sown Cereals

Any increase in lost time inevitably prolongs tillage and seed bed preparations which indirectly affects the timeliness of other operations by delaying their starting date. The most likely operations to be affected by a prolonged tillage operation are sowing or planting and harvesting operations. Despite the importance of the timeliness of harvesting, this phenomenon will not be studied in the current study as it is beyond the scope of this project.

The earliest possible sowing of spring cereals and the latest possible sowing of winter cereals reduces the peak demand for labour and machinery resources but at the expense of a considerable loss of grain yield. On a well managed enterprise, the value of grain yield foregone through late sowing must be equated with the advantages from having cheaper machinery and a smaller labour force. The importance of timeliness is reflected inthe wide range of investigations which have been conducted both in the U.K. and overseas. These studies have been carried out on different crops but because of the large variations of crops and the similarity of the pattern of timeliness penalty curves, only a few examples of studies on the effect of sowing date on the grain yield of wheat and barley are reviewed.

Spring Wheat

Forbes (1959) in his experiment, found that there was no effect of date of sowing on the yield from spring wheat. This is in marked contrast to the results from other studies. Short (1970) obtained a significant reduction in grain yield by delaying the sowing date from 15th February to 23rd March. Proctor (1973) also examined the effect of two dates of sowing on the yield of spring wheat and indicated that the weekly rate of yield reduction from the end of March was 125 kg/ha.

There is also data available on the crop response for date of sowing under American conditions. Woodward (1956), from the results of his experiment, concluded that early sowing for three years showed an increased yield of 64% while traditional dates of sowing averaged 32% higher yields than the later dates. For the same period an average of 36% reduction in grain yield was attributed to late sowing.

Winter Wheat

There is clear evidence in favour of early sowing of winter wheat under both British and overseas conditions. This can be attributed to the fact that early sowing provides a sufficient amount of time for crop establishment before ground frost is prevalent in some parts (U.K.) and crop maturity before the commencement of the drought season in other parts of the world (India). In a trial conducted at Norfolk, U.K., Mundy and MacClean (1965) observed a reduction of 470 kg/ha (3.75 cwt/acre) in the grain yield of winter wheat when the date of sowing was delayed from 2nd October to 17th November. Winter wheat planted on 19th November, 19th December and 19th January in the ADAS eastern region produced grain yields of 4.53, 4.1 and 4.98 t/ha (36.1, 32.7 and 39.7 cwt/acre), respectively. This experiment shows a yield increase for very late sowing - late January - of winter wheat (ADAS 1970). An experiment at seven different sites on ADAS Experimental Husbandry Farms showed that there always has been a considerable yield reduction by delaying the sowing date of winter wheat from late September or early October. Results of their experiment indicated an average of 790 kg/ha (6.7 cwt/acre) grain yield reduction by delaying the sowing date from 2nd to 24th October and 376 kg/ha (3 cwt/acre) by delaying until 19th November.

The effect of date of sowing on winter wheat grain yield was also examined at Gleadthorpe EHF (1973) and the result followed the expected pattern, i.e. there was a reduction of 800 kg/ha (3.5 cwt/acre) per month delay in the sowing date from September. In a study to find the optimum sowing date for winter wheat, Croxall and Smith (1964) concluded that the optimum sowing time lies between 10 and 45 days after the date on which the 09.00 h soil temperature at 10 cm (4 in.) depth first falls to 14°C (55°F). For their experiment, this day fell between late September and early October and any delay in sowing after this date showed considerable reduction on grain yield.

The results from three studies carried out in the U.S.A. were more variable. In some parts, date of sowing did not have a marked effect on grain yield (Honley et al, 1960) while, in other parts, a considerable decline in grain yield was recorded due to late sowing of winter wheat (Fenster et al, 1972). In the latter experiment which was conducted at Nebraska, wheat was planted on five dates: 20th August and 1st, 10th, 20th and 30th September. In general, grain yield was increased by delaying the sowing date up to 10th September but further delay resulted in a drop in yield. In another study in Alberta, Slykhuis et al (1957) also found a reduction in grain yield of winter wheat when it was sown after mid-September. They recommended early September as the best time for sowing winter wheat for that area.

The effect of sowing date of winter wheat on grain yield has also been studied in India. In a series of experiments in different parts of India, early October to the end of November was identified as the best time of sowing for winter wheat. During the years 1966-68 in a group of experiments at Powerkheda MP Research Station to find the effect of date of sowing dwarf and tall wheat on grain yield by Cupta et al (1968), five different times of sowing, namely, 10th and 25th October, 9th and 24th November and 9th December were examined. From the comparison of the results, it is understood the yield from that seed sown in November (2.7 t/ha) was significantly higher than for the other dates. Results from this experiment corroborated the results obtained by Mahanta (1967) who carried out a trial during 1961-62 in Madhepura Research Station to investigate effect of sowing date on grain yield of wheat. He quoted that significantly higher yields of grain (3.23 and 3.22 t/ha) were obtained when the crop was sown on 1st and 16th November as opposed to the ones sown on the later dates of 1st, 16th and 13th December (2.36, 15.7 and 0.92 t/ha).

Contrasting results were obtained by Nadagoudar and Patil (1973a and 1973b) from their two experiments. These experiments were carried out on different varieties of wheat under rainfed conditions. The results were almost similar and the conclusion drawn from both the experiments was that the crop sown on 10th October resulted in the highest grain yield compared with yields from crops sown on 1st and 15th September and 25th October.

Spring Barley

Sowing spring barley as early as possible ensures a significant increase in grain yield due to early establishment and early maturing which creates more flexibility for the harvesting operation and reduces possible crop damage through late harvesting or not harvesting at all. This has been proved by many research workers who have confirmed by experiment that there is always a grain yield reduction if spring barley is sown too late. Mundy and Page (1972) obtained an average of 920 kg/ha reduction in grain yield from April sown barley compared with the March sown crop. Short (1970) in his experiments, also obtained a reduction in grain yield of spring barley (425 kg/ha) by delaying the sowing date from 19th February to 26th March. Proctor (1973) found that the rate of yield reduction from each week's delay in sowing at the end of March and early April was 165 kg/ha/week. Walker (1975) observed a reduction of 880 kg/ha in grain yield when he delayed drilling barley from mid-January to 7th March. An increment of 687 kg/ha (5.5 cwt/acre) in grain yield was gained from barley sown early on 26th February compared with that sown late on 1st April by ADAS (1974b).

An average of 290 kg/ha reduction in grain yield was attributed to a delay in sowing date of spring barley from January to March at Gleadthorpe Experimental Husbandry Farm (Selman, 1974 and 1977). In a series of experiments carried out at ADAS West Midland EHF to examine the effect of date of sowing on spring barley grain yield, barley was sown on 12th March and 26th April in 1964. The result was an average reduction of 875 kg/ha (7.0 cwt/acre) due to late sowing. This experiment was repeated over a 5 year period with dates of sowing ranging from early March until mid-May and, in all cases, grain yield was depressed by delaying the sowing date. A full description of these trials is published in ADAS EHF Results, numbers 12-17 for 1964-69.

Winter Barley

The relationship between grain yield and sowing date of winter barley has not received such detailed scrutiny as spring barley. One important trial was carried out at Gleadthorpe EHF where winter barley was sown in mid and late November, early and late December and mid and late January. There was a slight yield reduction of 325 kg/ha (2.6 cwt/acre) when sowing was delayed until late December and a yield increase of 275 kg/ha (2.2 cwt/acre) when it was sown in mid-January (ADAS 1974a).

Results of these experiments were used to quantify the economic effect of date of sowing of cereals on the gross margin of the farm enterprise. Analysis of the data and existing equations are discussed in the next section.

3.11.4 Evaluation of Timeliness Penalties (Cost of Lost Time)

Hunt (1968) defined the timeliness as the "state of being opportune or optimum in field operations." Its benefit is evaluated by the cost of being untimely, that is, the cost experienced as a result of reduction in value of the crop because of yield, harvesting, marketing and quality losses.

In this study, the emphasis is placed on the timeliness of the sowing operation by assessing that the later primary tillage and seed bed preparation is completed, the greater the subsequent delay in sowing. The simplest approach of taking timeliness into account is to define a time period for the completion of an operation and choose the only machine systems which are capable of accomplishing the given job within the assigned period. In this procedure, no account is taken of the system completing the operation outside the assigned period and this may be an unduly harsh barrier in comparison with other selection criteria. Link (1967) proposed that the use of yield/time functions is the most comprehensive procedure to evaluate the timeliness cost. Sowell et al (1971) defined the timeliness function as a relationship between the time of performing some operation on a crop and some measure of output (e.g. return, yield, etc.). An example of yield/time function for winter wheat and spring barley is shown in Figure 3.7. The quadratic equation 3.16 is a typical yield/time function.

$$\text{YIELD} = \text{CY1} \times \text{TIME}^2 + \text{CY2} \times \text{TIME} + \text{CY3} \qquad 3.16$$

where CY1, CY2 and CY3 are coefficient depending on the crop type and location;

TIME is a measure of time, i.e. calendar day or week and/or time distance from a particular event, such as ripening;

YIELD is the amount of yield obtained at TIME.

By integrating equations 3.16 with respect to the TIME, the variation of the YIELD due to variation of the TIME can be evaluated. Data in section 3.11.3 was analysed in order to develop a yield/time function for British conditions and combined with this procedure used in the current study. Hunt (1968) and Hunt and Patterson (1968) suggested that the yield/time function can be represented by two straight lines, one on each side of the optimum point as shown in Figure 3.8. They defined a factor 'K' as "the decimal reduction of the quality and quantity of potential crop per hour of machine operation." The hourly cost of timeliness can be calculated by multiplication of the K factor with the area, yield and unit price of the crop. Another procedure for evaluation of timeliness penalties was proposed by Chancellor (1968). He suggested that the net value of crop production per day can be used by assuming that all year-round cropping is permitted. Dividing this value by the potential hours of work in a day will result in the timeliness costs in pounds per hectare per hour. This method is applicable to tropical conditions rather than to other climates. Sowell et al (1971) suggested that because of the strong dependence of timeliness on weather, machine breakdowns, and other uncontrollable factors, it should be treated as a stochastic process rather than a deterministic one. This will require considerable historical data on

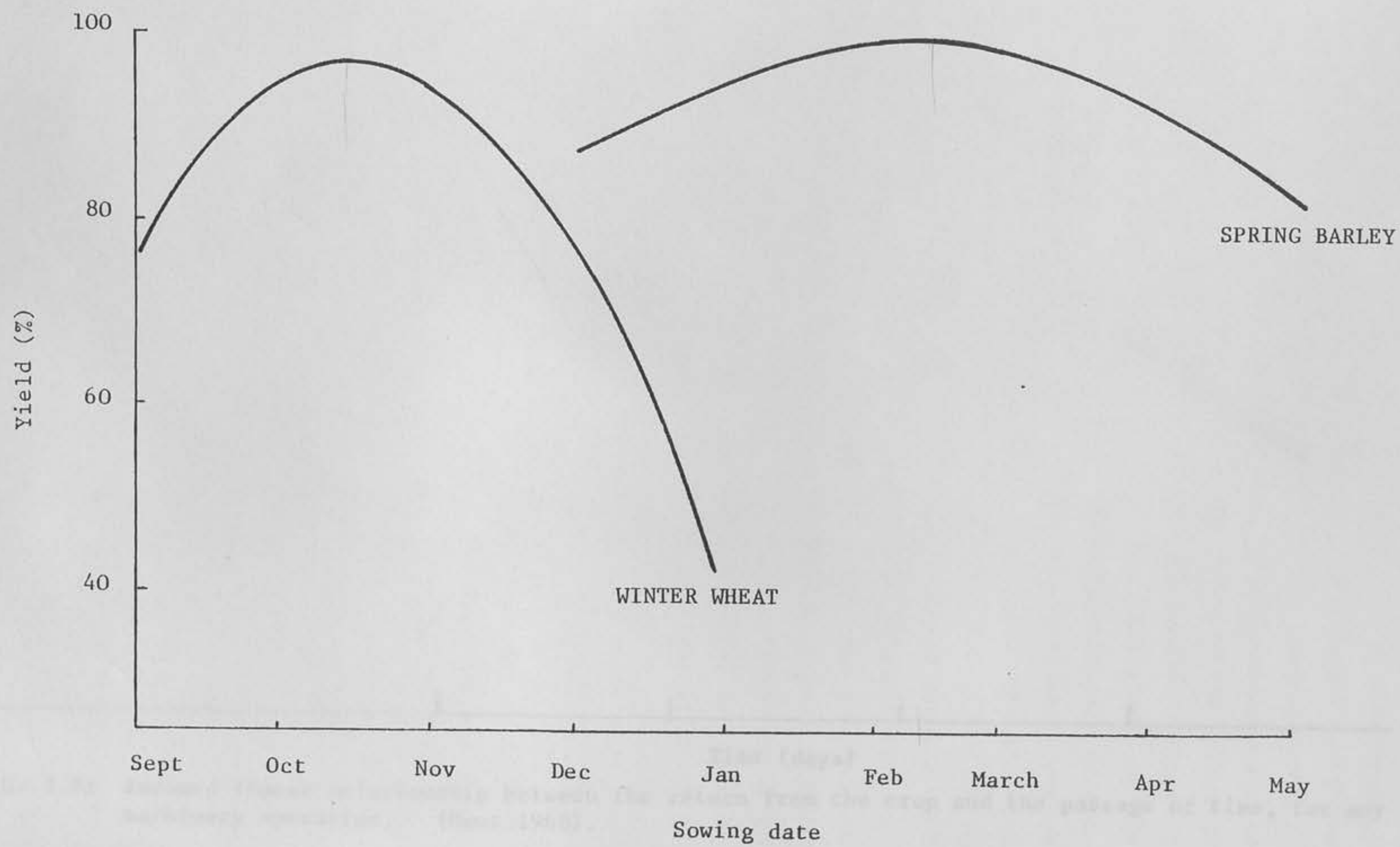

FIG. 3.7: Cereal timeliness penalties as a percentage of maximum yield.

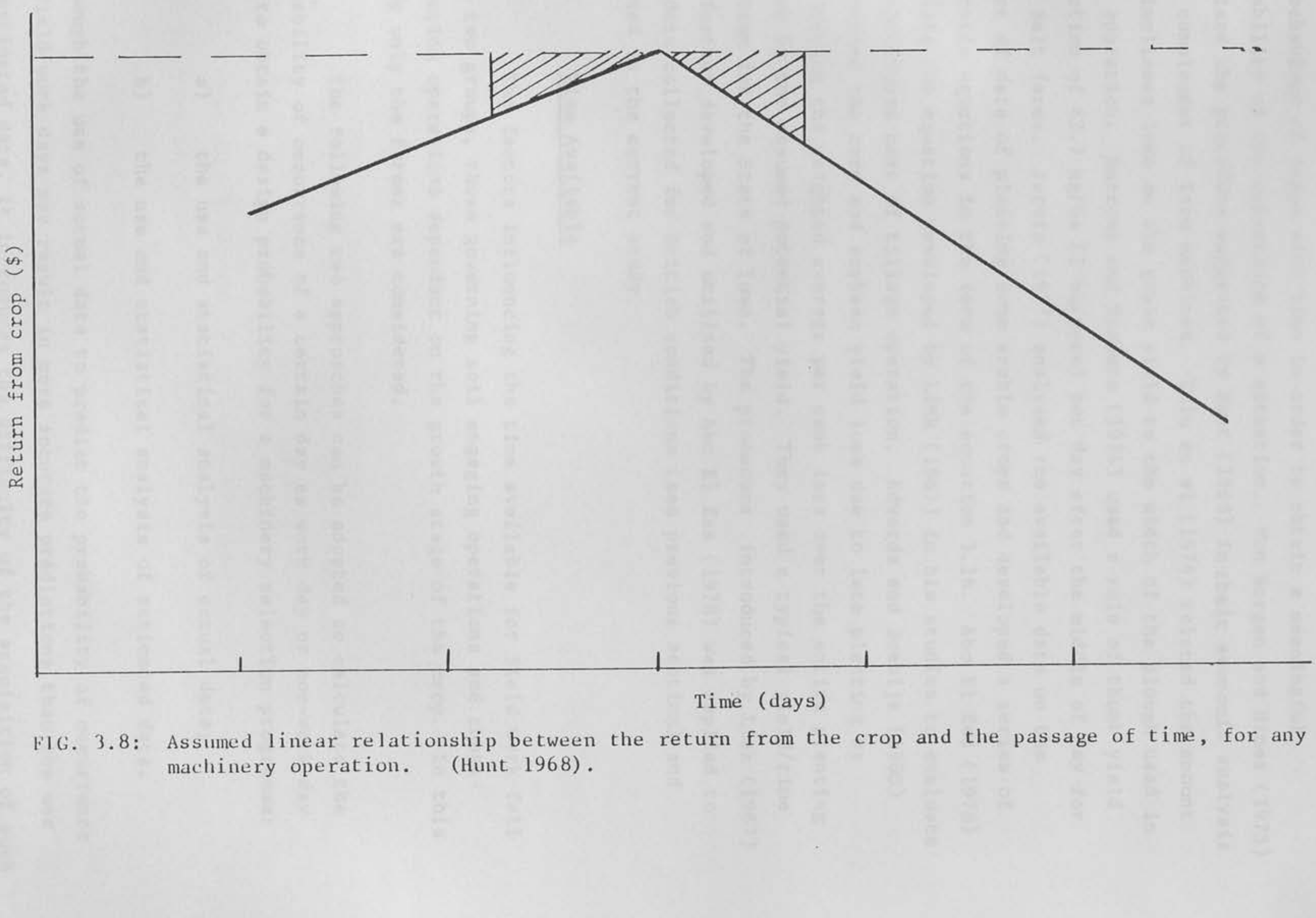

FIG. 3.8: Assumed linear relationship between the return from the crop and the passage of time, for any machinery operation. (Hunt 1968).

the behaviour of crops with time in order to obtain a meaningful probability of the occurrence of a situation. Von Bargen and Hines (1973) utilised the procedure suggested by Hunt (1968) in their economic analysis of a complement of farm machines. Tulu et al (1974) related the amount of timeliness loss on the grain yield to the width of the plough used in the operation. Burrows and Siemens (1974) used a rule of thumb yield reduction of 62.7 kg/ha (1 bu/acre) per day after the middle of May for Corn Belt farms. Jarvis (1977) analysed the available data on the effect of date of planting some arable crops and developed a series of quadratic equations in the form of the equation 3.16. Abo El Ees (1978) utilised the equation developed by Link (1967) in his studies to evaluate the timeliness cost of tillage operation. Edwards and Boehlje (1980) calculated the corn and soybean yield loss due to late planting by multiplying the weighted average per cent loss over the entire planting season by the assumed potential yield. They used a typical yield/time function for the State of Iowa. The procedure introduced by Link (1967) and further developed and utilised by Abo El Ees (1978) was applied to the data collected for British conditions (see previous section) and adopted in the current study.

3.12 Time Available

The factors influencing the time available for field work fall into two groups, those governing soil engaging operations and those affecting operations dependent on the growth stage of the crop. In this study only the former are considered.

The following two approaches can be adopted to calculate the probability of occurrence of a certain day as work day or non-work day and to obtain a design probability for a machinery selection programme:

a) the use and statistical analysis of actual data;

b) the use and statistical analysis of estimated data.

Although the use of actual data to predict the probability of occurrence of field work days may result in more accurate predictions than the use of estimated data, it introduces the difficulty of the acquisition of such data. Few farmers or other organisations have kept detailed records of the days on which they have actually worked or the field was suitable for a certain operation. These data are more available in the U.S.A. than in the U.K. Link (1962) analysed data recorded by an Iowa farm manager for the days on which a farm operation had been carried out in order to obtain a meaningful prediction procedure. Although the data were very comprehensive and covered a 30 year period, he concluded that these data are very restricted in their generality and applied only to the specific farm, which was typical of farms in the region. These types of data have often been used to estimate the number of spring and autumn working days for soil engaging operations. Hunt (1963) and Link (1968) used such data in their machinery planning programmes. Fulton et al, (1975) carried out a statistical analysis of work day data supplied by Iowa Crop and Livestock Reporting Service (ICLRS). Miller (1980) produced a summary of work day data which he used in his model to predict a minimum cost machinery complement for various farm situations. These data were available for 32 States of the U.S.A. for the period 1978-80. Edwards and Boehlje (1980) used the actual data produced by Ayres and Williams (1976) instead of using estimated data.

Estimation of soil workability and trafficability from other measured or recorded variables is a common practice in the development of machinery selection programmes.

Daily measurements of soil strength, moisture tension and moisture content over a long period (at least 5 years) can provide sets of basic data for the prediction of both soil workability and available work days. These data are also rarely available and even if they exist, they are only applicable to the area from which they have been collected.

The most practical way of predicting available days for soil engaging work is to use readily available meteorological and soil data.

For some time, meteorological data alone have been used as a means of predicting the number of available days for field work. Duration and intensity of precipitation has often been used as a restricting factor for assigning a day as a work day or as a non-work day. The duration of daylight, the air temperature (severity of frost), the wind velocity and the occurrence of drought also influences the amount of available time for field work. The effect of the duration of daylight can either be accounted for or eliminated by producing artificial lighting. Wind velocity and air temperature usually are accounted for in most of the soil moisture prediction models and as for extreme air temperature and strong winds, a risk factor can be incorporated if the frequency of their occurrence has been too high in the past.

Precipitation has often been used as an indicator of soil workability. Smith (1966a) defined a dry day for these different soils as follows:

For heavy soil a day with $\leqslant$ 1.27 mm (0.05 inch) rainfall was a dry day until late April and thereafter the criterion for a dry day was $\leqslant$ 2.25 mm (0.09 inch). This criterion for a medium loam was 1.77 mm (0.07 inch) until mid April and 2.25 mm afterwards.

For a light soil he used a criterion of 2.23 mm rainfall a day throughout the spring.

A year later, Smith (1967) applied these criteria in addition to another restricting factor of freezing temperature at $0^{\circ}C$ ($32^{\circ}F$) to a set of independent data of spring cultivations at Gleadthorpe EHF over a ten year period. Another method of using rainfall data alone to predict available days for soil engaging operations was described by Jeffers and Staley (1968). They used the criteria of 1.27 mm (0.05 inches) rainfall on the day and 1.27 mm (0.05 inch) rainfall on the day before. They substantiated these predictions by field observations obtained for 1965 and 1966. In 1968, Smith (1968) simplified the criteria used in his previous works (Smith, 1966 and 1967). He carried out these modifications in the light of more actual data obtained for 1967. Jose (1971) using the analytical criteria in Table 3.2, classified the calendar days into the following three categories: 0-type days, no field operation can be performed; 1-type day, only certain tasks can be performed; 2-type day, any operation can be performed. Smith (1972a) in a study to evaluate the effect of weather, drainage efficiency and duration of spring cultivation on barley yields in England, analysed the official meteorological office rainfall data recorded over 20 years in order to obtain the number of predicted available days for tillage and cultivation. Smith (1972b) re-examined the data presented in his previous works (Smith, 1966, 1967, 1968) to obtain the number of days required to achieve a given number of field work days.

TABLE 3.2 Classification criteria for fieldwork activities based on rainfall

Amount of Rainfall (R) inches/day	Fieldwork That Day	1st Day Following	2nd Day Following	3rd Day Following	4th Day Following
$R < .25$	2	2	2	2	2
$.25 \leq R < .5$	0	1	2	2	2
$.5 \leq R < 1.0$	0	0	1	2	2
$R \geq 1.0$	0	0	0	1	2

after: Jose, D. (1971)

The most widely used approach to obtain an estimate of days suitable for soil engaging operations is the conversion of weather data such as rainfall into the soil physical data such as soil strength, plasticity and moisture content. Several approaches have been adopted to relate the weather variables to soil variables and obtain a fair prediction of soil physical conditions from meteorological data. While these procedures will be discussed in the later stages of this study, the various criteria used to assign a day as a work day based on soil physical and mechanical properties are of immediate relevance.

3.12.1 Soil Workability Criteria

A soil is workable if a) it has sufficient compressive strength to withstand the weight of the machine and, b) it has sufficient shear strength to meet the traction requirement with acceptable wheel slip and soil damage and c) a suitable tilth can be produced.

Bolton et al (1968) in a study to develop a model for soil work-day prediction used two measures of woil water level defined by Broadfoot and Burke (1958), namely, 'field maximum' and 'field minimum'. They classified a day as a work day if the soil moisture in the surface 150 mm (6 in.) layer was 80% of field maximum for tillage operations and 85% for non-tillage operations for silty clay and sandy soils. No explicit definition of the two terms of 'field maximum' and 'field minimum' was given in their paper. The terms 'field capacity' and 'wilting point' has often been used to represent these measures. Rutledge and MacHardy (1968) and Rutledge and Russell (1971) compared the two different criteria of 95% and 99.5% of field capacity as a soil moisture content level above which the performance of a tillage operation was not possible and concluded that the difference between the number of available days for these two criteria was not significant. Frisby (1970) assigned a day as 'bad' (non-work day) when the soil moisture content was above the field capacity. Morey et al (1971) suggested that a day was a work day when the moisture content of the soil in the top 152 mm (6 in.) profile did not exceed 95% of the available capacity (amount of water held betwen field capacity and the wilting point) and when less than 2.5 mm (0.1 in.) of rainfall had fallen, Smith (1972c) classified a day as a work day when the sum of the water removed by drainage and evaporation was greater than the amount of rainfall which had occurred on that day. In another study to predict autumn work days, Smith (1972d) used an additional criterion of drainage time as well as the previous criteria (Smith 1972c). Selerio and Brown (1972) used the criterion of 90% of field capacity in a loam soil. Baier (1973) used a set of different criteria for different zones of the soil as shown in Table 3.3. Hassan and Broughton (1975) in a study to establish a standard criterion for soil workability reviewed most of the available literature, emphasised the need for the use of standard terminology and pointed out the occasion on which different terms have been used synonymously while they had different meanings. In order to avoid this confusion, he summarised the criteria for seed bed preparation for three different soils in terms of both percentage of field capacity (FC) and available water capacity (AWC). These criteria are presented on Table 3.4. Soil moisture deficit both in terms of mm of water content and mm of tension has also been used as a criterion for soil workability. 3000 mm of moisture suction in the top 500 mm of soil was regarded as the limit for soil workability by Wind (1976). Smith (1977) used values of 3.2 and 1 mm of soil water deficit on the topmost soil layer as a threshold for workability of heavy soils and medium and light soils, respectively.

Elliot et al (1977) based the soil workability criterion used in their model on both soil moisture content and rainfall. Values of 70-95% of F.C. and 0.51 mm of rainfall were considered the maximum limit for soil workability. These criteria were also used by Wendte et al (1978). Dyer and Baier (1979a) suggested that the air temperature also has to be taken into account when defining soil workability criteria as well as soil moisture content and rainfall.

TABLE 3.3 Criteria for a field workday based on estimated soil moisture in the upper three zones.

Soil Moisture Notation	Zone	Depth of zone (inches)	Field capacity (F.C.) (inches)	Workday criteria: no snow on ground % of F.C.
SM 97.5	1	0-2	0.40	97.5
	2	2-6	0.60	97.5
	3	6-10	1.00	97.5
SM 90/95	1	0-2	0.40	90.0
	2 and 3	2-10	1.60	95.0

after: Baier (1973)

TABLE 3.4 Tractability criteria for seedbed preparation - Macdonald Farm, June 1973

Soil zone	Depth (cm)	B (FC%)	A (AWC%)
	Clay		
1	0-2.54	66	10
2	2.54-7.62	99	97
	Clay Loam		
1	0-2.54	60	50
	2.54-7.62	95	93
	Sandy Loam		
1	0-2.54	70	66
2	2.54-7.62	98.5	98.2

after: Hassan and Broughton (1975)

Despite the existence of various soil workability criteria, a criterion which can be generally applied for different soil types, different machines and different operations has yet to be found. A procedure suggested by Woorhees and Walker (1976), although not very comprehensive, can be used as a base for the development of a more comprehensive and generally applicable criterion for soil workability.

They suggested that suitable soil moisture content level for a soil engaging operation can be obtained by equating tractor pull predictions and implement draught prediction equations. This procedure in conjunction with economic factors is adopted in the current study to obtain a soil workability criterion.

3.12.2 Soil Moisture Content

By accepting the assumptions firstly, that soil moisture content is the only or the main factor affecting soil workability and secondly that daily measurements of soil moisture content by means of either a gravitational technique or by the neutron scattering method is laborious, tedious and time consuming, the prediction of soil moisture content is favoured as the obvious alternative for soil workability assessment. Soil moisture prediction models can be studied under the following five categories:

modulated budgets;	versatile budgets;
regression models;	analogue models;
meteorological models.	

Modulated budgeting is a procedure in which either a single soil zone is assumed or multiple zones are considered on the assumption that moisture removal in a lower zone will not start until the entire available water is removed from the upper zone. This procedure has been widely adopted through the past decade. The first attempt to utilise this approach was made by Penman (1948). He budgeted soil moisture losses against soil moisture supplies, analysed factors affecting soil moisture content, suggested that the evaporation process was the most effective factor and proposed a model to estimate evaporation from meteorological data. Krimgold (1952) also analysed the factors affecting soil moisture content and, in another study, (Krimgold, 1954), proposed a qualitative equation which balances all types of water entering the soil against the water leaving the soil. In a given segment of soil, rain, melted snow, irrigation water, surface run-off onto the segment, water condensing in the soil from the air entering the soil, water entering the segment as subsurface liquid flow from the adjoining soil and the amount of water moving into the segment from the adjoining soil were identified as factors increasing soil moisture content and surface run-off from the segment, amount of water leaving the segment as subsurface liquid flow, amount of water within the segment changing from water to vapour, evapotranspiration and interception by trees and vegetation were considered the factors decreasing soil moisture content. Based on this theory, Mather (1954) calculated soil moisture content for Ithaca, N.Y. and College Park, Md. and obtained a good agreement between measured and estimated values of soil moisture content.

Thornthwaite and Mather (1959) developed a series of computational tables by means of which soil moisture depletion under varying rates of evaportranspiration for soils holding different amounts of water at full capacity can be predicted. They obtained satisfactory results in a comparison of the estimated values of soil moisture content by means of these tables with the measured values for Ohio and some other locations. This approach has also been adopted by Shaw (1963) to estimate soil moisture under a corn crop, Ligon et al (1965) to estimate occurrence of a soil moisture deficit or excess, Pierce (1966) to estimate soil moisture under corn; meadow and wheat, Link (1968) to identify the research needed for farm machinery selections, Elliot et al (1977) to predict available days for soil tillage, Broughton and Forloud (1978) to predict water table depth for flat lands and, finally, by Wendte et al (1978) to evaluate the timeliness benefit of subsurface drainage.

The second procedure is the use of a versatile budget first introduced by Baier and Robertson (1966). In this method it is assumed that water is withdrawn simultaneously from different depths of the soil profile permitted by roots in relation to the rate of potential evaporation and available moisture in each zone. Another feature of this model is that the soil profile was divided into six soil moisture zones holding 5.08 mm (0.20 in), 7.62 mm (0.30 in), 12.7 mm (0.5 in), 25.9 mm (1.00 in), 25.4 mm (1.00 in) and 25.4 mm (1.00 in) of soil water holding capacity. This model was later employed by Rutledge and MacHardy (1968) and Rutledge and Russell (1971) to investigate the influence of the weather on field tractability in Alberta and on the prediction of work-day probabilities for tillage operation in the same area. Baier (1973) and Dyer and Baier (1979a) based their estimation of field working days in Canada and the number of field workdays in autumn, respectively, on the versatile moisture budget of Baier and Robertson (1966). Tulu et al (1979) combined this method by the procedure suggested by Shaw (1963) to evaluate the timeliness costs and predict the available working days for shelled corn. Despite the advantages of this model, its use was restricted to the areas for which detailed meteorological data for a long period were available.

The third source of soil moisture contents is to analyse experimental data and to correlate the soil moisture content with other available or easily accessible pertinent variables. This procedure was introduced by Carlson et al (1956). They related the soil moisture accretion and depletion to rainfall, amount of available pore space moisture level in the layer and season. They found that soil moisture accretion was strongly correlated with rainfall and available pore space. Soil moisture depletion on the other hand was found to be correlated with moisture level in the layer and with the season. The use of this procedure is also limited to the area from which the original data is obtained and worldwide application of this method requires an extensive experimental programme for every location.

Analogue models also have been used for the estimation of soil moisture content. While the analytical procedure is similar to that for the regression methods, the data is collected from the experiments carried out under simulated conditions either in a wind tunnel (Frisby, 1970) or from vessels containing soil (Wind, 1976). The extensive experimental data required to obtain a viable equation also restricts the worldwide application of these procedures.

The use of multipliers (factors) either arbitrary or based on weather data has also been suggested as a means of predicting the soil moisture content from meteorological data. Blaney and Criddle (1950 and 1962) used a factor derived from the daily sunshine hours and potential daylight to obtain a model to predict consumptive use of water for crops from which the remaining water in the soil can be predicted. Smith (1977) used models based on this theory which he introduced in 1967 MAFF (1967) to estimate the soil moisture deficits under grass and compared the results with the data obtained by the neutron probe. Multipliers are available for different parts of the U.K. and may be available for some other countries but as their worldwide existence is questionable, so is their use.

Of the procedures described here, the first procedure is the most commonly used, easily applicable and simple to calculate. It requires simple and basic meteorological data which are available almost in every climatological station. This procedure was adopted in the current study. The simplified form of the equation suggested by Krimgold (1954) which is utilised in this study consists of the following elements:

precipitation;	evapotranspiration;
surface run-off;	drainage.

Precipitation

The term precipitation is used as a combined name for all kinds of moisture which falls to the ground such as, rain, sleet and snow. Most of the researchers have involved that portion of snow which is melted in a given day as a part of precipitation for that particular day. Daily measurements of precipitation are usually taken in almost every climatological station.

Evapotranspiration

This term which is widely used in agricultural and hydrological sciences is the sum of the amount of water evaporated from the soil surface and the amount of water transpired by vegetation under a varying soil moisture regime. It is usually calculated from the potential evaporation (PE) or evaporation from sea levels and/or evaporation from an open water pan. The terms "actual evaporation" and "evapotranspiration (ET)" will be treated as synonymous in this study. Some researchers

(Baier and Robertson, 1966; Tulu et al 1979) have used actual recorded values of daily potential evaporation which is obtainable from some stations but this is not always possible because long term records of daily potential evaporation are not always available. The use of nationwide pre-determined tables such as the tables presented in MAFF (1967) provides another alternative for the calculation of potential evaporation but the over-generalisation of the data which is available and the lack of such data for many countries impose restrictions on their use.

In view of these limitations and acknowledging the importance of evapotranspiration (ET) in any water balance equation, it is essential to have a good, simple and accurate model in order to obtain an accurate evaporation data from simpler and more available meteorological data. Numerous procedures have been developed and three major classifications of existing methods have been suggested as follows:

a) Kijne (1974) classified the existing methods to calculate evaporation and evapotranspiration under:

- methods based on energy considerations
- methods based on empirical relationships

b) In the same year, Shnitnikov (1974) in Russia reviewed the existing methods for calculation of PE and ET under the following three categories:

- direct experimental observations and applications of empirical equation to the obtained data;
- calculation of evaporation as a residual member of water or heat balance equations;
- calculation methods based on theoretical assumptions, these methods being referred to as turbulent diffusion or mass transfer methods.

c) In a very recent study, Bahiran (1979) studied the existing methods for the calculation of PE and ET under the following two categories:

- empirical methods;

- combination methods.

For the purpose of the current study, current methods for the calculation of PE and ET are classified under:

theoretical and combination methods;

empirical methods.

Theoretical and Combination Methods

These methods are mainly based on theoretical assumptions, primarily on the Dalton formula and energy and water balance approaches. Energy balances are applicable to evaporation through the energy requirement for the phase change from liquid to vapour.

The theory of turbulent transport of water over a smooth or rough surface has widely been used as a tool for the estimation of evaporation from soils and vegetation. This theory was first introduced by Taylor (1917) and further experiments were conducted by Pasquill, (1943) to verify its applicability to estimate PE and ET. In a further study, Pasquill (1949a) provided data on some of the features involved in the turbulent transport of water vapour over a surface of short grass and on the validity of the formulae describing natural evaporation in terms of meteorological factors for adiabatic conditions. In another study, (Pasquill, 1949b) the validity of the formulae was tested for non-adiabatic conditions. In order to obtain actual data to obtain a satisfactory comparison of theory with practice, Pasquill (1949c) introduced a portable apparatus for the study of the humidity and the temperature profile near the ground. He resumed his investigation in the spring of 1949 with the aims of justifying more firmly the methods adopted for evaporation measurement and carrying out these and other relevant measurements for a range of grass length

(Pasquill, 1950). Calder (1939) had departed from the theory of turbulent transport of water vapour by introducing some empirical changes as a result of laboratory tests. Later on, Calder (1949) introduced a semi-empirical approach to estimate evaporation from aerodynamically smooth and rough areas. This study was extended by Deacon (1949) and applied to two different types of natural land surface.

Almost at the same time as these studies were being conducted another approach was being examined in Rothamsted. This procedure which later was termed as the combination method employs both the theory of turbulent transport of water vapour and that for the heat balance phenomenon introduced by Angstrom. Penman (1948) pioneered the development of this type of equation by introducing a semi-empirical equation which links PE to the net flux of radiant energy at the surface and to the effective ventilation of the surface by air in motion over it. In other words, it uses aerodynamics and the heat balance equation. Penman's (1948) equation has been revised several times by either the author himself or other researchers. Buhiran (1979) suggested that more than twenty different forms of Penman's equations can be found in the literature. Penman, (1952) revised his equation in order to incorporate a crop and day length factor which makes the equation applicable to ET from vegetation as well as evaporation from soil and water surface. In another, Penman, (1956) carried out an introductory survey of methods available for the calculation of PE and ET and identified major factors affecting these processes. Businger (1956) carried out another modification by concentrating on the empirical factors of Penman's equation. He replaced the empirical factor relating to wind velocity and surface roughness by a theoretical equation in order to improve its general applicability. Wesseling (1960) developed a series of tables to facilitate quick solutions of Penman equations. This equation was utilised by M.A.F.F. (1967) to calculate potential evaporation for different parts of the U.K. Later nomographs were produced by Koopman (1969) to enable rapid utilisation of Penman's equations. Baars (1973) extended the tables produced by Wesseling (1960). Linacre (1977) presented a simplified form of Penman's equation which used only the latitude, elevation and daily maximum and minimum temperature. Thom and Oliver (1977) revised

Penman's formulae, proposed a generalised ventilation term and derived a modified equation for evaporation.

Empirical Methods

These methods which describe the existing relationships between PE and other pertinent variable(s) are obtained by means of experimental data and do not necessarily agree with any theory. Three major categories can be identified in the study of these methods.

The first category contains the models which are based on temperature and day length. The first method in this series was developed by Thornthwaite (1948) and utilised mean monthly temperature and actual hours of sunshine. Because of its simplicity in terms of both data requirement and concept and its successful application for many different climates, this procedure has been widely used in different countries. Palmer and Havens, (1958) developed a graphical procedure to facilitate the calculations required in using this procedure. Pierce (1958) used these equations to estimate seasonal and short term fluctuations in evapotranspiration from meadow crops. Blaney and Criddle (1950) introduced another procedure based on air temperature and day length. This procedure has been widely accepted as a tool for estimation water requirements of crops and prediction of irrigation frequency. (Blaney and Criddle, 1962).

The second category are models based on temperature and radiation. A formula developed by Turc (1954) predicts the amount of PE for a given air temperature and radiation on a ten day basis. Nomographs are also available to carry out calculations (Kijne 1974). Jenson and Haise (1963) proposed another method based on these principles. These models tend to underestimate the PE during the spring and overestimate during the summer months.

The third category consists of the methods which are based on other weather and soil variables such as the graphical procedure devéloped by Staple and Leharce (1944) and used by Staple (1956). This procedure relates the amount of removable water from the soil to the amount of recorded rate of potential evaporations from the open water surface by means of family of curves for each rainfall event. Another procedure in this category is the procedure suggested by Black et al (1969) which successfully predicted the PE from bare sand for an entire season by using only rainfall and irrigation input. A comprehensive review of these models are produced in works written by Shnitrikov (1974) and Buhiran (1979).

Of the methods described here some are more comprehensive and produce more accurate results (Penman, 1948 and Pasquill, 1943) than others (Thornthwaite, 1948 and Blany and Criddle, 1950) which are very simple and produce less accurate estimation of evaporation. The applicability of the first group is restricted by their extensive and detailed data requirements while the latter group require some sacrifice of accuracy to achieve general applicability. As the application of the current study to Iran is intended and predictions made by Thornthwaite (1948) procedure compared satisfactorily with the data published by MAFF (1967), this procedure was adopted for the purpose of the current study.

Calculation of Actual Evapotranspiration

Actual evapotranspiration (hereafter will be referred to as ET) according to Kijne (1974) is "the actual amount of vapour transferred to the atmosphere, which depends not only on existing meteorological conditions but also on availability of water to meet atmospheric demand and, in the case of vegetation, its ability to extract moisture from the soil."

ET can either be directly measured or calculated from actual or predicted values of potential evaporation (PE). Weighable and non-weighable lysimeters and atmometers can be used for direct measurement of ET (Kijne, 1974). Procedures for the calculation, estimation and measurement of PE have been discussed in detail (see previous section). In this section, procedures available to calculate ET from PE will be examined.

Pierce (1958) identified two factors to compensate for soil dryness and crop stage of growth as being important in the calculation of ET, but, in another study, Pierce (1960) added two more factors to adjust for length of day and the frequency of rainy days. Gerb (1966) introduced the fifth factor, namely, a crop percentage factor or surface coverage factor which is more important in the case of row crops. By taking these factors into account, Pierce (1960) proposed an equation by means of which the PE can be adjusted in order to obtain ET. This equation was revised to incorporate the fifth factor, surface coverage, to give the final form:

$$ET = PE \times DC \times CC \times LC \times RC \times SC \qquad 3.15$$

where ET and PE are defined before;

DC is dryness correction factor;

CC is crop stage correction factor;

LC is the length of day correction factor;

RC is the rainy day correction factor;

SC is the surface coverage correction factor.

Numerous methods have been suggested for the calculation of the soil dryness correction factors. Literature on this subject is voluminous, only a few important procedures will be discussed here.

If the rest of the correction factors are kept constant, the value of DC is:

$$DC = \frac{ET}{PE} \qquad 3.16$$

and it is also a function of soil moisture content (M).

$$DC = f(M) \qquad 3.17$$

Four different suggestions have been made regarding the shape of this relationship.

I - A step wise decrease of DC from 1 as the soil moisture content (M) decreases, was first proposed by Hapkias et al (1955). The simplest form of this relationship is DC = 1 when M is greater than permanent wilting point (PWP) and DC = 0 when M < PWP (Figure 3.9a).

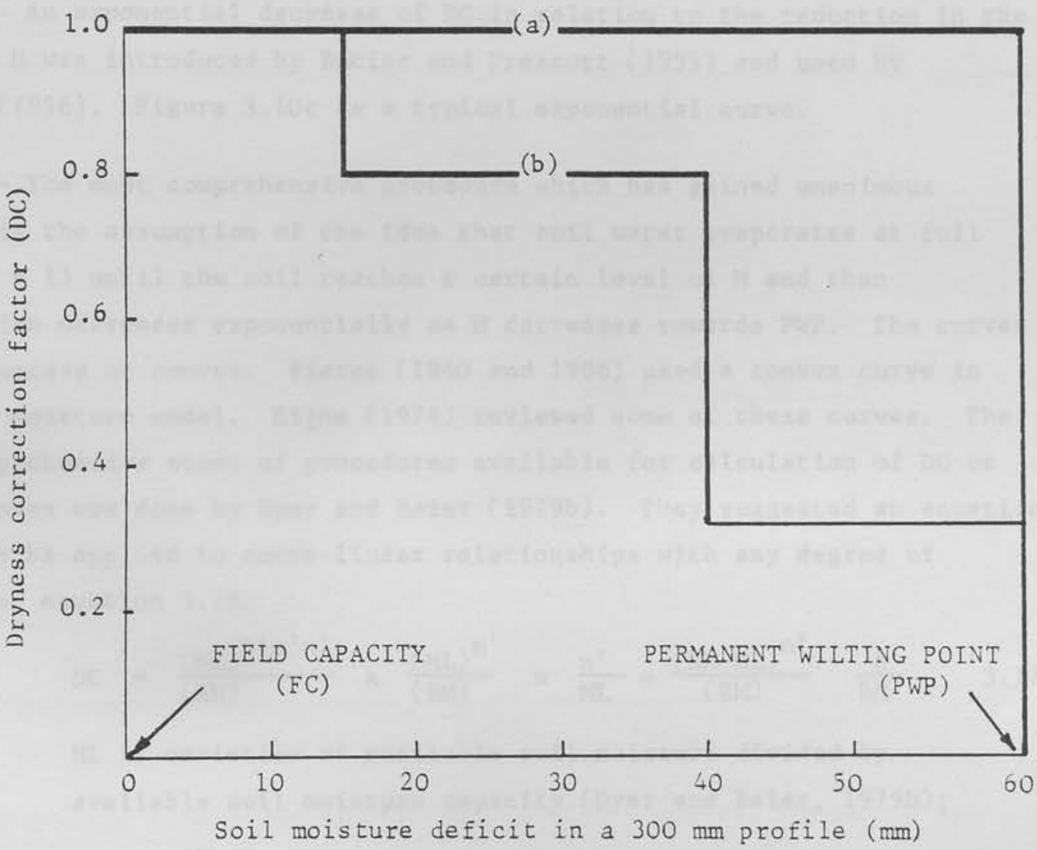

FIG. 3.9: Dryness correction factor (Stepped)

Expanding the number of steps, Pierce (1958) proposed that DC1 = 1 until the soil reaches a certain level of $\overset{1}{M}$ (15 mm deficit), drops to DC2 = 0.80 after the moisture decreases to a value of M2 (45 mm deficit) and eventually reaches to its lowest value of DC3 = 0.32 when M3 is at the level of 63 mm deficit (Figure 3.9b).

2 - A linear decrease of DC from 1 as soil moisture content M decreases from field capacity (FC) to either PWP or to oven dryness (OVD) is also wholly supported (Figures 3.10a and b). Makkink and Van Heemst (1956), Marlatt et al (1961), Link (1968) and Baier (1969) all adopted this procedure.

3 - An exponential decrease of DC in relation to the reduction in the value of M was introduced by Butler and Prescott (1955) and used by Slatyer (1956). Figure 3.10c is a typical exponential curve.

4 - The most comprehensive procedure which has gained unanimous support is the assumption of the idea that soil water evaporates at full rate (DC = 1) until the soil reaches a certain level of M and then evaporation decreases exponentially as M decreases towards PWP. The curves can be concave or convex. Pierce (1960 and 1966) used a convex curve in his soil moisture model. Kijne (1974) reviewed some of these curves. The most comprehensive study of procedures available for calculation of DC or drying index was done by Dyer and Baier (1979b). They suggested an equation which can be applied to curve-linear relationships with any degree of curvature, equation 3.18.

$$DC = \frac{(ML)^{h'm'n'}}{(RM)} \times \frac{(ML)^{m'}}{(RM)} \times \frac{n'}{ML} + \frac{(RM-ML)^{n'}}{(RM)} \quad \frac{n'}{RM} \qquad 3.18$$

where: ML is varieties of available soil moisture divided by available soil moisture capacity (Dyer and Baier, 1979b);

RM is a point of ML until which DC = 1;

h', m' and n' are control factors depending on the type of curve.

All the existing curves and lines are special cases of equation 3.18 with different combinations of h', m' and n'. Different combinations of h', m' and n', relevant simplified equations and corresponding curve numbers (Figure 3.11a and b are given in Table 3.5. A curve of type (1) with control factors of

$m' = 1$, $n' = 1$ and $h' = 0$ was found to be suitable for Scottish soils and the following simplified equation was adopted in this study.

$$DC = \frac{2RM-ML}{RM^2} \qquad 3.19$$

All variables used in equations 3.18 and 3.19 are dimensionless.

TABLE 3.5 Combinations of control parameters used in equation 3.18 to generate different drying curves and the form that equation 3.18 is reduced to in each case.

Curve Shape	m	n	h	Expression for DC	Curve No
Concave	1	1	0	$\frac{2\ RM-ML}{RM^2}$	(1)
Convex	1	1	1	$\frac{2RM \times ML-ML^2}{RM^3}$	(2)
Deeply Convexed	1	1	2, 3 and 4	$\frac{2RM \times ML^{h'} - ML^{h'+1}}{RM^{h'+2}}$	(4,5 and 6)
Linear	1	1	0	$\frac{1}{ML}$	(2)
Potential	0	1	0	$\frac{1}{RM}$	

after: Dyer and Baier (1979a)

Crop storage correction factor (CC) is also a crucial factor in the calculation of ET from PE. Pierce (1959) used a curve similar to the one shown on Figure 3.12 for meadow crop to obtain the variation in the amount of crop water use at successive stages during the growing season. He adopted this procedure in his later work (Pierce 1960). In another study Pierce (1966) introduced similar curves for corn and wheat and these correction factors, with some adjustment, were used in the current study.

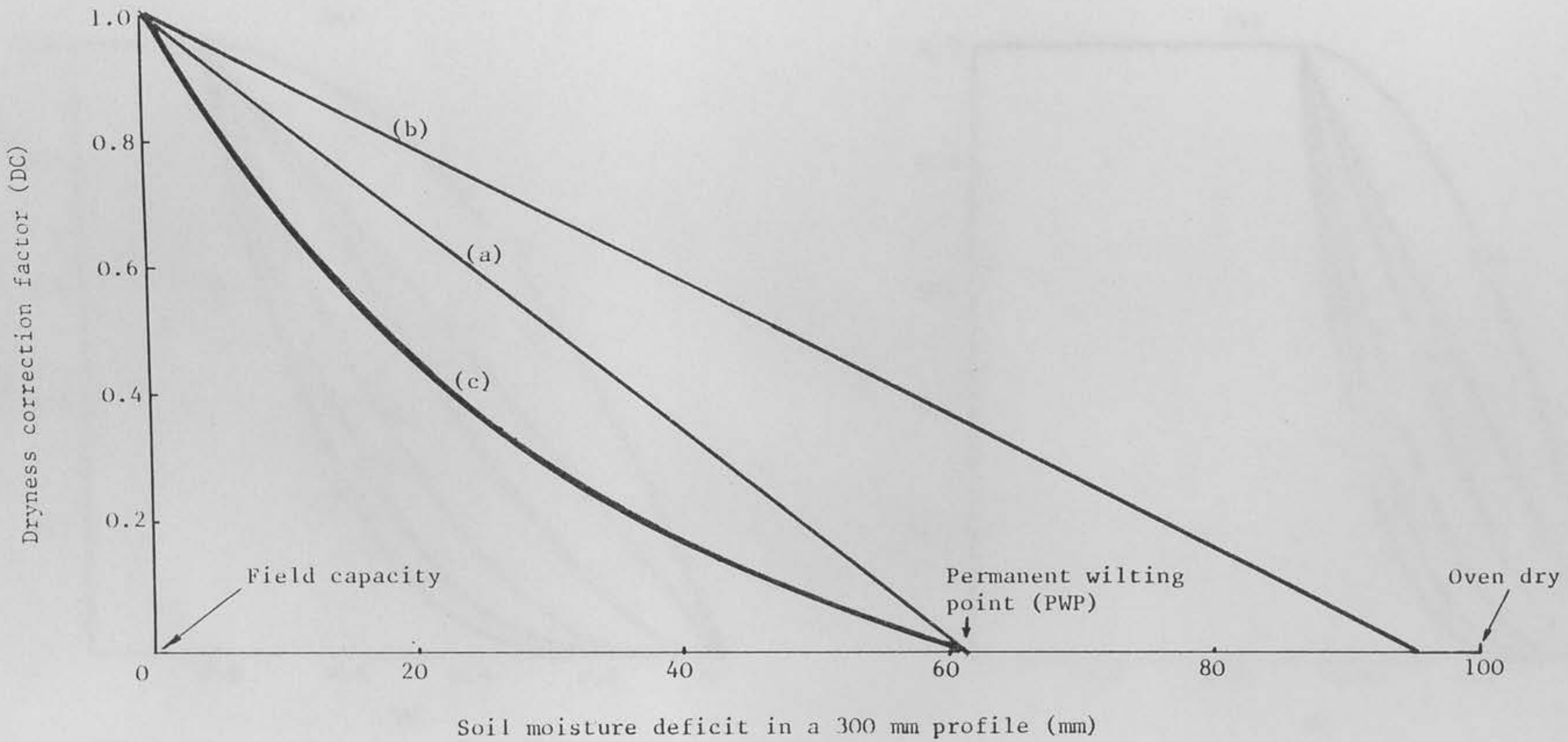

FIG. 3.10: Dryness correction factor (Linear).

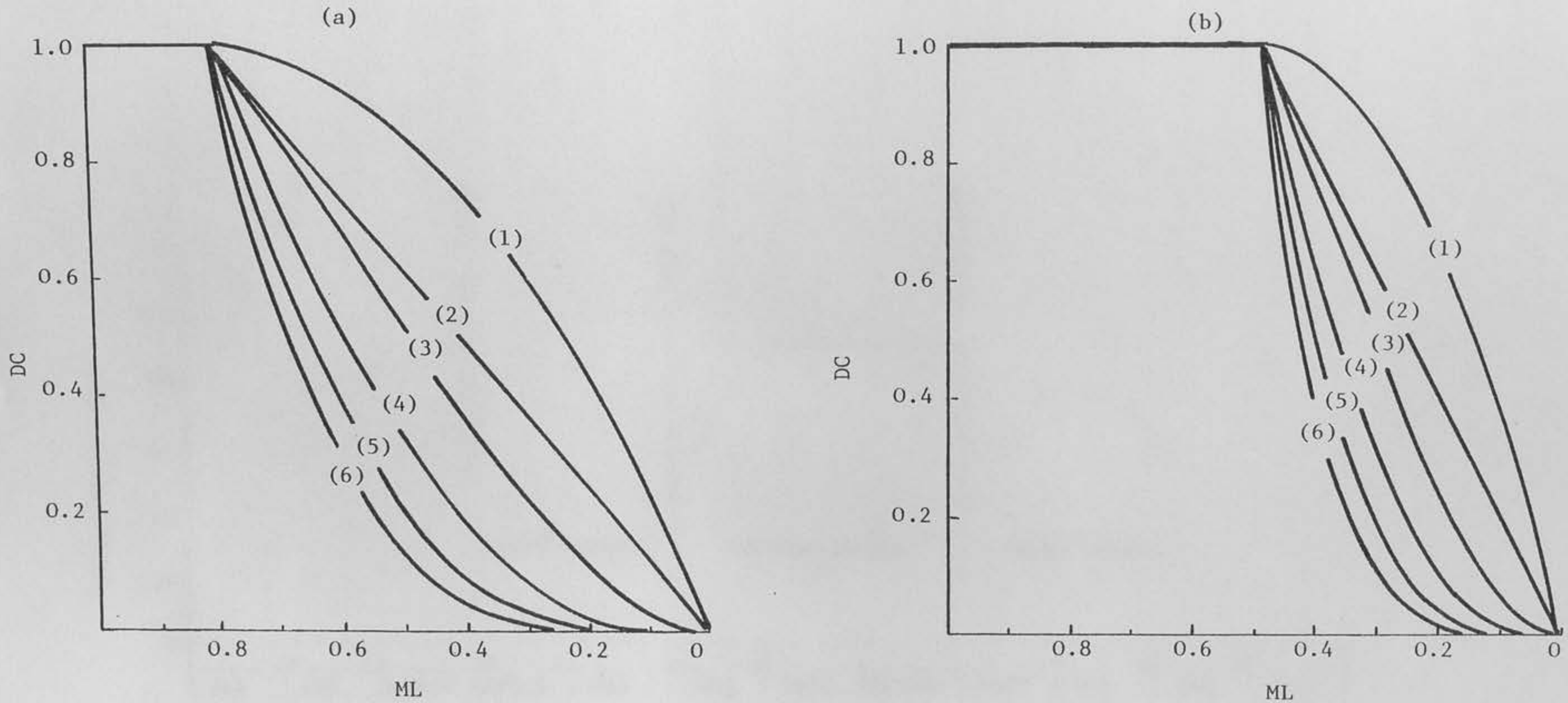

FIG. 3.11: Drying curves derived from the proposed index for

(a) RM = 0.8 and (b) RM = 0.5 (Dyer and Baier 1979)

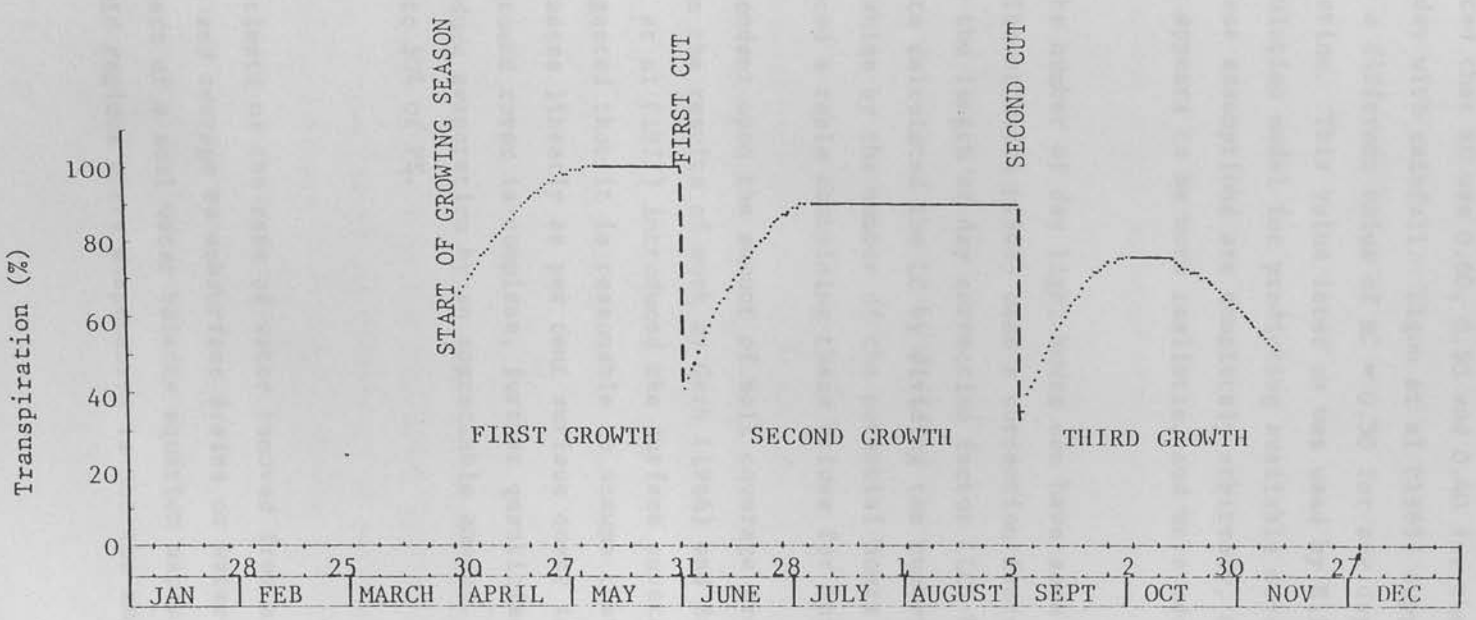

FIG. 3.12: A typical crop storage correction factor for seasonal crops (Source: Pierce, 1960).

The occurrence of measurable rainfall in a particular day resulted in an increase of humidity and cloudiness and in a decrease of air temperature, all of which have a retarding effect on the rate of actual ET. Pierce (1960) introduced the rainy day correction factor (RC) to compensate for these effects. He suggested that RC was 0.60, 0.50 and 0.40 for the first, second and any successive day with rainfall. Ligon et al (1965) supported this conclusion and used a different value of RC = 0.50 for any day with measurable precipitation. This value later on was used by Elliot et al (1977) in their simulation model for predicting available days for tillage. Although both of these assumptions are completely arbitrary, the values suggested by Pierce appears to be more realistic, and were adopted for current study.

Variation of the number of day light hours can have some effect on the amount of ET. Thornthwaite (1948) used a correction factor which later on was termed the length of day correction factor (LC) by Pierce (1960). Thornthwaite calculated the LC by dividing the number of the actual hours of sunshine by the number of the potential hours of sunshine. Pierce (1966) produced a table containing these values for Ohio.

ET is also dependent upon the amount of soil coverage provided by crop residues. From the results of work by Gerb (1966) and Bond and Willis (1969,1970), Elliot et al (1977) introduced the surface coverage correction factor (SC) and suggested that it is reasonable to assume that the rate of evaporation decreases linearly as per cent surface cover is increased up to 100%. Once ground cover is complete, further quantities of residue do not appear to reduce evaporation by an appreciable amount. At most, the ET was reduced to 50% of PE.

Drainage

An accurate estimate of the rate of water removed from a soil profile by deep percolation and seepage to subsurface drains or water reservoirs form an essential part of a soil water balance equation especially in temperate and humid regions where evaporation is not the most influencial factor.

The easiest and the most popular procedure for the estimation of water flux through the drainage process is the use of a drainage coefficient. That is, to assume that the excess water gained by soil through precipitation or irrigation will be removed from the soil at a constant rate until the soil reaches the field capacity (FC). This procedure, although inaccurate and oversimplified, has been widely used for varying purposes. Roe and Ayres (1954) used drainage coefficients to obtain the water flux rate for tile drainage. Sitterley and Bere (1960), Elliot et al (1977) and Dyer and Baier (1979a) utilised these coefficients in their models for soil workability prediction. Another use of drainage coefficients has been made by Shaw (1963), Wendte et al (1978) and Broughton and Foroud (1978) in the development of soil moisture prediction models.

Empirical methods have also been suggested to predict the rate of water discharged through drain gauges. Koshal (1934) used the data obtained for 55 years in Rothamsted Experimental Station in a statistical analysis in order to obtain a regression equation between drainage rate and pertinent variables. He chose rainfall, air temperature and another two variables which were products of these variables and time. These procedures have restricted use due to the variations of soil, climate and other factors with different locations. Richards et al (1956), from the results of their experimentations, related the rate of change of soil water content at different layers with the passage of time and proposed the following exponential equation to represent the data:

$$M = a_3 t^{b_3} \qquad 3.20$$

where, a_3 and b_3 are a coefficient and an exponent, respectively, depending on the soil type and soil layer, M is the soil water content (% w/w,g/g) and t is the passage of time (days). A derivative of equation 3.20 will result in the soil water loss due to drainage. Wilcox (1960) utilised this theory in his studies and found restrictions in its use and inconsistencies between the measured and calculated results. In contrast, Miller and Aarsland (1974) calculated soil water depletion by this method and obtained a good agreement between calculated and measured results.

Darcy's law has also been widely applied to the problems of steady and non-steady flow of water through the soil profile:

$$\mathrm{DRAIN} = -K\left(\frac{d\phi}{d\,hi} - 1\right) \qquad 3.21$$

where: DRAIN is the soil water flux or drainage water, K is the hydraulic conductivity of soil, ϕ is the soil water pressure head and hi is the soil depth measured downwards positively.

Eegeleman and Jamison (1962) from the results of their experiments concluded that, in a uniform soil underlaying a freely drained soil variation of soil water pressure head with changes in the depth $\left(\frac{d\phi}{d\,hi}\right)$ was negligible and the hydraulic gradient was near unity. This conclusion was later on supported and used by Black et al (1969), Davidson et al (1969), Baver et al (1972) and Clothier et al (1977) in their studies. By taking into consideration the above conclusion, equation 3.21 can be reduced to the very simple form of:

$$\mathrm{DRAIN} = K \qquad 3.22$$

Another school of researchers have adopted Richards' (1931) formula which is a combination of Darcy's law and equation of continuity.

$$\frac{d\theta}{d\,t} = \Delta.\,(K.\Delta P) \qquad 3.23$$

where θ is volumetric water content of the soil (cm^3/cm^3), P is a potential function (Richards, 1931) and K and t are as previously defined.

This equation was later on simplified by Childs and Collis-George (1950) for one dimensional horizontal flow:

$$\frac{d\theta}{d\,t} = \frac{d\,\theta}{d\,x}\left(K(\theta)\,\frac{d\,\theta}{d\,x}\right) \qquad 3.24$$

and one dimensional vertical flow

$$\frac{d\theta}{d\,t} = \frac{d}{d\,h}\left(K\,\frac{d\,\theta}{d\,hi}\right) + \frac{d\,K(\theta)}{d\,hi} \qquad 3.25$$

where, x and hi are horizontal and vertical distances from a fixed reference point, respectively.

Other variables have been defined previously.

Equation 3.24 and 3.25 have been successfully used to calculate the vertical and horizontal flow of water through the soil. Gardner (1959) solved equation 3.24 for the estimation of the drying of soils and other porous media. Ashcroft et al (1962) presented a numerical solution of equation 3.24 for horizontal flow in a semi-infinite media.

Equation 3.26 was applied to simulate one dimensional water movement through unsaturated non-homogenous soils (Wang and Lakshminarayana, 1968) and two-dimensional, transient flow of water in unsaturated and partly saturated soils (Rubin 1968).

The successful application of equation 3.22 by many researchers, (Black et al, 1969; Davidson et al, 1969; Baver et al, 1972; and Clothier et al, 1977) in the past and the results of practical experiments by the author justified the use of this equation in the current study.

The hydraulic conductivity (K) used in equation 3.22 has been related to volumetric and gravimetric soil moisture content and numerous data are available to enable the establishment of the type of their relationships. Many researchers from a wide range of experiments throughout the world are unanimous in the existence of an exponential relationship between hydraulic conductivity (K) and volumetric water content (Θ) (Gardner, 1956; Brust et al, 1968; Wang and Lakshminarayana, 1968; Kunze et al, 1968; Davidson et al, 1969; Cassel, 1975, Carvallo et al, 1976 and Parkes and Waters, 1980). The same type of relationship has also been reported between K and soil water tension by Denning et al (1974). The general form of equation can be written as:

$$\ln K = a_4\Theta + b_4 \qquad 3.26$$

where a_4 and b_4 are constants dependent on the soil type and physical characteristics.

After thorough examination of the available data (Cassel, 1975) and analysis of a field experiment, it was concluded that a_4 and b_4 can be related to the soil physical properties such as soil water content at saturation (M_{sat}) and at field capacity (M_{fc}) and hydraulic conductivity at saturation (K_{sat}) and at field capacity (K_{fc}). These variables are either readily available from the literature or can easily be measured. The final form of the equation and its application will be discussed in Chapter 4 of this study.

Run-Off

Run-off is defined as "that portion of the rainfall that is not absorbed by the deep strata, utilised by vegetation or lost by evaporation and which finds its way into the streams as surface or subsurface run-off" (Roe and Ayres, 1954). The main factors influencing rate and volume of surface run-off are size, geology, shape and topographic characteristics (including slope) of the watershed; rainfall intensity and duration; type of vegetal cover; soil type and surface roughness; general drainage conditions over the watershed and seasonal and climatic factors. In addition to these factors, the physical properties of the subsoil and the extent and effectiveness of the sub-drainage also influence the subsurface run-off.

The size of watershed is the most influential factor in determining the volume and rate of surface run-off. Three major size groups are identified and different procedures are adopted for the estimation of run-off from each size group. These size groups are large, medium and small watersheds.

Large watersheds are those which cover a large area such as an entire drainage basin of a great river. Run-off volume from these basins are usually estimated by means of hydrographs. The unit hydrograph method which is mainly used for the estimation of the run-off rate and volume from large watersheds was first introduced by Sherman (1932). The basis of this method is the unit graph which is the hydrograph that would result from a 25.4 mm (1 inch) run-off from the entire watershed following uniform rainfall lasting one unit of time. A detailed description and application of this method is presented by Rousse (1950).

Medium watersheds are the ones which cover the drainage basins of relatively small rivers, branches and streams embracing up to 250 km^2.

Empirical procedures such as the formula suggested by Meyer (1928) relate maximum flood flow from the watershed to the area, characteristics of watershed and frequency of rainfall.

Small agricultural watersheds (Roe and Ayres, 1959) are the ones which cover areas of up to 500 ha of arable land and are considered the most important watersheds for agricultural activities. For the purposes of the current study, therefore, a detailed examination of procedures available for the estimation of run-off from these watersheds will be carried out. Techniques employed for the estimation of run-off volume from these watersheds fall into two categories of rational and empirical methods.

The rational method was introduced by Ramser (1927) and has been widely employed in the prediction of run-off volume from small watersheds (Ramser et al, 1929). In this procedure, run-off was related to the area of the watershed, intensity of rainfall and a coefficient which is dependent on the characteristics of watershed. Infiltration theory was also used to develop run-off prediction equations (Cook, 1946). Baier and Robertson (1965) used infiltration theory combined with the data from the work by Linsley et al (1949) and developed a logarithmic equation relating run-off to rainfall and infiltration. Rate of infiltration was related to rainfall and available soil moisture.

Empirical methods have also been developed for estimating run-off from pertinent variables using either graphical or regression correlation techniques. Linsley et al (1949) applied the principles of graphical correlation, especially the co-axial method introduced by Ezekiel (1941) to relate surface run-off to antecedent precipitation index, season or week of the year, storm duration and storm rainfall. The co-axial method of graphical correlation is based on the premise that if any important factor was omitted from a relation then the scatter of points in a plot of the observed values of the dependent variable versus those computed by the relation will be at least partially explained by the omitted factor (Linsley et al, 1949). The choice of the parameters and the development of the required graphs are described in a paper by Kohler and Linsley, 1951. Buss and Shaw (1960) applied the information provided by Kohler and Linsley (1951) to develop another graph which later on was used by Shaw (1963). Another example of the application of graphical techniques for the prediction of run-off is the method developed by the U.S.D.A. at the Soil Conservation Service, Region III (1948). This procedure also uses the antecedent precipitation index. The original method was further refined by Betson et al (1969) in order to reduce the number of parameters and inter-relationships.

Conventional regression methods have also been adopted in order to obtain regression coefficients between rate of run-off and other pertinent variables. Hartman et al (1960) developed an empirical equation for the prediction of run-off volume from antecedent soil moisture characteristics and rainfall. The term antecedent soil moisture (ASM) was introduced by Hartman et al (1958) and used as an indicator of soil moisture condition at the time when run-off is being computed. Antecedent soil moisture used in this study is the amount of water (mm) retained above permanent wilting point of the soil (PWP). Relationships expressed in this procedure, although empirical, are compatible with physical interpretations. Despite the restrictions involved in the generally applicability of any empirical relationship, the limited data required and the satisfactory application of the equations to independent data justified their use in the current study. This model was further developed by Knisel et al (1969) to overcome some of the shortcomings of the original model. The development and use of the model will be discussed in detail in the following section. Fogel (1969) proposed an empirical method for the prediction of the effect of rainfall variability on run-off from small semi-arid watersheds. He related run-off to the mean storm rainfall and an exponent with a function of distribution time. Run-off also was found to be a quadratic function of daily rainfall, a linear function of soil water content and an inverse function of rainfall intensity (Hauser and Hiller, 1975). The conclusion was expressed in the form of a regression equation and was used to predict run-off volume for fallow fields by Hauser and Hiller (1975).

4. THEORY AND METHODOLOGY

In this chapter the emphasis will be placed on the background, development and application of actual equations, methods or techniques utilised in the development of the tractor selection model. Procedures adopted from other research will be reviewed briefly and new methods developed by the author will be discussed in detail. The following steps were taken to select optimum power level for tillage operations:

1 prediction of tractor performance (predictions of pull produced);

2 prediction of implement performance (predictions of draught required);

3 matching the tractor with the implement;

4 calculation of work rate or productivity;

5 prediction of time required for completion of the task;

6 prediction of time available for completion of the task;

7 calculation of the timeliness penalty;

8 calculation of the total costs of the operation;

9 optimisation of the total costs and timeliness costs.

4.1 Prediction of Tractor Performance

The amount of pull produced at the drawbar of the tractor was calculated by means of empirical equations developed at the N.I.A.E. These equations which were initiated by Dwyer et al (1974a) and further developed by Dwyer et al (1974b) relates tractor performance characteristics to wheel mobility number (WMN) introduced by Freitag (1965) and improved by Turnage (1972). These equations, as reported by Gee Clough (1977), are as follows:

$$CT = CT_{max}\,(1\text{-}\exp(-ks)) \qquad 4.1$$

where: CT = coefficient of traction or pull/load;

CT_{max} = coefficient of traction at maximum efficiency;

k = rate constant

s = wheel slip

CT_{max} and k and s are related to wheel mobility number (WMN) as follows:

$$CT_{max} = 0.796 - \frac{0.92}{WMN} \qquad 4.2$$

$$kCT_{max} = 4.837 + 0.061\ WMN \qquad 4.3$$

$$s = 9 + \frac{19}{WMN} \qquad 4.4$$

The coefficient of rolling resistance for the front wheels CRR_f is also calculated from WMN by means of the following relationship:

$$CRR_f = 0.49 + \frac{0.287}{WMN} \qquad 4.5$$

The tractive efficiency (TE) was found from the following equation:

$$TE = \frac{CT\,(1 - s)}{CT + CRR} \qquad 4.6$$

or in terms of WMN:

$$TE = 78 - \frac{55}{WMN} \qquad 4.7$$

WMN is a dimensionless number and expresses a relationship between tyre dimensions, weight and deflection and soil strength (cone index). The development of this number has been discussed in detail in section 3.7.2 and only the final form of the equation is reproduced here:

$$WMN = \frac{CI\ bd}{W} \sqrt{\frac{\delta}{h}} \times \frac{1}{1 + \frac{b}{2d}} \qquad 4.8$$

where: WMN = wheel mobility number;

CI = mean cone penetrometer resistance (kN/m^2 or kPa);

b = tyre section width (m);

d = tyre undeflected diameter (m);

W = vertical load carried on tyre (kN);

δ = tyre deflection under load (m)

h = tyre section height (m).

Tyre dimensions, weight and deflection data used to calculate WMN were obtained from the NIAE Handbook of Tyre Performance (Dwyer et al 1976) and Dwyer (1980). Cone index, although easily measurable, was related to soil moisture content and bulk density and successfully predicted from these variables. Adoption of this procedure provided the ability to predict tractor performance at varying levels of soil moisture content in order to obtain the amount of pull produced at a given level of soil moisture content. The equation used is:

$$CI = 450.5\, M^{-2} + 0.019 V \qquad 4.9$$

where: M = soil moisture content (mm of water at 300 mm of soil profile)

V = soil specific weight (kN/m^3)

This relationship was obtained for three typical Scottish soils over a wide range of soil moisture contents.

4.2 Prediction of Implement Performance

Considerations were based on the development and use of an equation which can predict the performance characteristics of the implement demanding the highest drawbar pull, namely, the plough. From the literature review and the analysis of field data, a comprehensive equation was developed, tested and used in this model. This equation takes into account the soil moisture, specific weight and strength, plough dimensions and travel speed. This equation was based on the equation developed by Goryachkin (1940) and adopted by Söhne (1960) to express the relationship between plough draught requirement and speed, as follows:

$$Z = Z_o + \varepsilon v^2 \qquad 4.10$$

where: Z = specific draught;

Z_o = quasi static component of specific draught;

V = actual speed; $V = V_o (1 - s)$, V_o = no-slip speed

s = slip

ε = factor

The factor, ε, depends mainly on the lateral directional angle θ' at the mouldboard tail, such that:

$$\varepsilon = K (1 - \cos \theta') \qquad 4.11$$

where K is a constant.
Another form of equation 4.10 which contains a component for the soil moisture content percentage (M) was developed by Woorhees and Walker (1977) such that:

$$Z = -2.572 M + 106.503 + 0.2450 V^2 \qquad 4.12$$

Gee-Clough (1977) used the dimensionless groups of variables affecting plough draught which were suggested by Krastin (1973) to model plough performance. The following equation was originally proposed by Krastin (1973):

$$\frac{D}{a^2} = f\left(\frac{w}{a}, \frac{\gamma a}{\sigma}, \frac{ga}{V^2} \right) \qquad 4.13$$

D = plough draught force;

a = depth of cut;

w = width of cut;

V = speed;

g = gravitational constant;

γ = soil specific weight;

σ = soil stress;

f = function of.

Correlation was sought between the dependent term of $\frac{D}{aw}$ and the other dimensionless groups (π terms). Different expressions containing cone index, cohesion, soil density, internal friction angle and soil metal friction angle were tried for the stress term and a significant correlation was found between the stress term, σ, and cone index CI such that:

$$CI = \sigma \qquad 4.14$$

Later, this term was eliminated to yield the final form of the equations:

$$\frac{D}{aw} = K_3 \left(\frac{\gamma a}{\sigma}\right) + K_4 \left(\frac{\gamma a}{\sigma}\right)\left(\frac{V}{ga}\right) \qquad 4.15$$

By substituting values for K_3 and K_4, the predictive equation used by Gee-Clough (1977) is:

$$Z = \frac{D}{aw} = 13.3\,\gamma\,a + 3.06\,\frac{\gamma V^2}{g} \qquad 4.16$$

Elimination of the stress term, σ , from the predictive equation precludes the effect of cohesion, and, therefore, the effect of changing soil moisture content on the draught requirement of the plough. In the light of these restrictions and from a knowledge of soil mechanics, an equation is proposed which is based on a combination of a quasi-static draught component using Coulomb's soil strength equation with cone index values substituted for the cohesive and frictional parameters and dynamic draught component which incorporates the effect of plough tail angle. The equation is:

$$Z = \frac{D}{aw} = K_5 C\bar{I} + K_6\,\gamma V^2(1 - \cos\Theta')/g \qquad 4.17$$

K_5 and K_6 are constants and their values were found to be 0.05 and 9.66, respectively, from the regression analysis of N.I.A.E. data and further confirmed from data obtained from the experimental results. The following equation was used to predict plough draught:

$$D = 0.05\,a\,w\,C\bar{I} + 9.66\,a\,w\,\gamma V^2(1 - \cos\Theta')/g \qquad 4.18$$

By means of equation 4.9 and 4.18, plough draught was predicted from the soil moisture content, soil specific weight and speed.

4.3 Matching the Tractor with the Implement

Four criteria are used for matching the tractor with the implement, namely:

a) the pull produced by the tractor should either equate or exceed the sum of the draught of the plough and the rolling resistance of the front wheels of the tractor;

b) the tractive efficiency is not less than an acceptable level of 65%;

c) the weight/power ratio is not greater than 100 kg/kW per driving wheel;

d) the soil damage due to smearing and soil compaction does not exceed a certain limit. The actual pull delivered by each driving wheel was calculated from:

$$PULL = W \times CT \qquad 4.19$$

and for two wheels or a tractor:

$$APULL = \sum_{n=1}^{2} W_n \; CT_n \qquad 4.20$$

Using equation 4.1:

$$APULL = \sum_{n=1}^{2} W_n \, (CT_{max})_n \, (1 - e^{-kns}) \qquad 4.21$$

To satisfy the criterion (α), APULL calculated from equation 4.21 must be greater than or equal to the sum of the draught required, equation 4.18 and the rolling resistance of the front wheels or towing force from equation 4.5, i.e.:

$$APULL = D + RR_f \qquad 4.22$$

Therefore $\sum_{n=1}^{2} W_n \, (CT_{max})_n \, (1 - e^{-kns}) = (0.05 \; a \; w \; Cl + 9.66 \; a \; w \gamma V^2$

$$(1 - \cos \theta')/g + \sum_{n=1}^{2} (W_f)_n \, (CRR_f)_n \qquad 4.23$$

where: W_f is the weight on the front wheels.

To satisfy condition (b), the tractive efficiency of the two tyres or the tractor was calculated by means of the following form of the equation 4.6:

$$TEF = \frac{\sum_{n=1}^{2} CT_n \, (1 - S)}{\sum_{n=1}^{2} CT_n + \sum_{n=1}^{2} CRR_n} \qquad 4.24$$

Criterion (d) was accounted for in criterion (b) and (c) when these criteria were satisfied, the theoretical pull or gross pull is calculated by means of the following equation:

$$TPULL = APULL \times TEF \qquad 4.25$$

and the tractor power was calculated from the theoretical pull.

$$POWER = TPULL \times V \qquad 4.26$$

Another restriction (e), was imposed in order to prevent the selection of too large a tractor for too small a task and that was:

$$APULL \leqslant 1.3\ (D + RR_f) \qquad 4.27$$

4.4 Calculation of Work Rate

The work rate of the plough is calculated from the travel speed and plough dimensions:

$$PAFC = 0.1\ a\ V\ NB\ PFE \qquad 4.28$$

where: PAFC = work rate of the plough (ha/h);

a = width of the plough (m);

NB = number of plough bodies;

V = actual speed with slip (km/h);

PFE = plough field efficiency.

4.5 Time Required

The amount of time required to complete the job is calculated by dividing the area of the field by work rate:

$$HOURS = \frac{AREA}{PAFC} \qquad 4.29$$

and days required

$$DAY = \frac{HOURS}{PHOUR} \qquad 4.30$$

where: PHOUR is the number of potential working hours per day.

4.6 Prediction of Time Available

1 a day is chosen as a smallest unit of time;

2 soil moisture content was the main factor preventing soil engaging operations;

3 Saturdays, Sundays and public holidays were assumed to be workdays if soil moisture condition was satisfactory;

4 effect of air temperature (frost) was accounted for through its effect on water removal;

5 tractor was available if soil conditions were suitable;

6 operator was readily available.

With these assumptions in mind, a soil moisture prediction model was developed utilising partly the results of other researchers and partly the results of experiments carried out by the author. The model is a simulation model and based on the qualitative soil moisture balance equation proposed by Krimgold (1954) which is: 4.31

$$\Delta M = PR + CA + (RUN_I + RUN_O) + (DRAIN_I - DRAIN_O) + (VAP_I - VAP_O) - (ET + INT)$$

where: PR = precipitation

ΔM = variation of soil moisture at a given segment of soil;

CA = amount of water condensing on the soil from the air entering the soil;

RUN_I, RUN_O = surface run-off onto and from the segment of relief;

$DRAIN_I$, $DRAIN_O$ = amount of water entering and leaving the segment as subsurface liquid flow ;

VAP_I, VAP_O = amount of water vapour entering and leaving the segment;

ET = evapotranspiration; evaporation from the soil and ponded water and transpiration by vegetation;

INT = interception by trees and vegetation.

This expression was simplified for the purpose of this study and the following form is used to obtain amount of soil moisture level at the end of day, n, in a 300 mm deep soil segment.

$$M_n = M_{n-1} + PR_n - ET_n - DRAIN_n - RUN_n \qquad 4.32$$

where: M_n = soil moisture extent at the end of day, n, (mm of water in 300 mm soil);

M_{n-1} = soil moisture content at the end of the day prior to day, n (mm H_2O/300 mm);

PR_n = amount of precipitation at the end of day, n, (mm/day);

RUN_n = amount of surface run-off from the soil at the end of day, n (mm/day);

$DRAIN_n$ = amount of subsurface drainage at the end of day, n, (mm/day);

ET_n = amount of evaporation from soil and ponded water and transpiration by vegetation at the end of day, n, (mm/day).

M_{n-1} is assumed to be equal to the amount of soil moisture content at field capacity or when soil moisture tension is 0.33 bar. PR_n is available in almost every climatological station or it can easily be measured with the aid of a rain gauge.

Evapotranspiration, ET_n, was calculated from potential evaporation and corrected for the dryness of the soil, humidity of the air, cloudiness, stage of crop and percentage of soil surface cover. The equation suggested by Pierce (1960) was converted in order to incorporate the correction factor for soil surface cover as follows:-

$$ET_n = PE_n \times DC \times LC \times RC \times CC \times SC \qquad 4.33$$

where: PE_n = potential evaporation for day, n, (mm/day);

DC = soil dryness correction factor;

LC = length of day correction factor;

RC = rainy day correction factor;

CC = crop stage correction factor;

SC = surface cover correction factor.

PE_n or potential evaporation was calculated from mean monthly air temperature data using Thornthwaite's (1948) method. The equation yields accumulated potential evaporation for a 30 day month. Daily values of evaporation were obtained simply by dividing the monthly evaporation by the number of days in a standard month, thirty.

The formulae is:

$$PE_m = 16\ (10T/I)^A \qquad 4.34$$

where:

$$A = (0.675I^3 - 77.1I^2 + 0.017920I + 492390) \times 10^{-6} \qquad 4.35$$

$$I = i_1 + i_2 + i_3 \ldots\ldots i_{12} \qquad 4.36$$

$$i = (T/5)^{1.514} \qquad 4.37$$

T = mean monthly air temperature

PE_m = monthly evaporation

$$PE_n = \frac{PE_m}{30} \qquad 4.38$$

Soil dryness factor, DC, was calculated using the procedure suggested by Dyer and Baier (1979b) which assumes a value of DC = 1 until a certain level of soil moisture deficity, RM, after which DC declines in a parabolic curve as the soil moisture deficit increases. The general equation, its control factors and related figures are given in equation 3.18, Table 3.5 and Figures 3.10 - 3.11 in section 3.12. A special case of this equation which was used by Pierce (1960) and confirmed with experimental results was used as follows:

$$DC = \frac{2\ RM - ML}{RM^2} \qquad 4.39$$

where: DC is previously defined;

ML is varieties of available soil moisture divided by available soil moisture capacity (Dyer and Baier, 1979b);

RM is a point of ML until which DC = 1.

The length of day correction factor, LC, was calculated by dividing the number of actual hours of sunshine per day by the number of potential hours of day light. The former was obtained from meteorological stations and the latter was extracted from the Smithsonian Tables for a given latitude (List, 1966) or:

$$LC = \frac{ASN}{PDL} \qquad 4.40$$

where: ASN = actual hours of sunshine recorded;

PDL = potential daylight hours obtained from Smithsonian Tables (List, 1966).

The rainy day correction factor, RC, was obtained from Table 4.1 as suggested by Pierce (1960).

TABLE 4.1 Rainy day Correction Factor

Number of consecutive days with precipitation	Rainy day correction factor, RC
0	1
1	0.75
2	0.65
3 and more	0.55

The crop stage correction factor, CC as proposed by Pierce (1966) for meadow and cereals were obtained from Figure 3.12 and Table 4.2, respectively. The effect of soil surface cover on evaporation is also accounted for by using a soil surface cover correction factor, SC, proposed by Gerb (1966), that is the rate of evaporation decreases linearly as the per cent surface cover (PSC) increases to 100%,

$$SC = -0.005\ PSC + 1 \qquad 4.41$$

Once ground cover is completed, further quantities of residue do not appear to reduce evaporation by an appreciable amount.

Drainage, $DRAIN_n$, which is the amount of water lost from the soil at the end of the day, n, is calculated from the hydraulic conductivity of the soil in accordance with Darcy's equation:

TABLE 4.2: Crop Stage Correction factor, CC, for Wheat (Pierce, 1966)

Month					
April	May	June	July	August	September
.80	1.00	1.00	.57	.62	.88
.82	1.00	1.00	.54	.63	.88
.84	1.00	1.00	.52	.64	.88
.86	1.00	1.00	.49	.66	.88
.88	1.00	.99	.47	.67	.88
.90	1.00	.99	.45	.69	.88
.91	1.00	.98	.44	.71	.88
.93	1.00	.98	.42	.73	.88
.94	1.00	.97	.41	.74	.88
.95	1.00	.97	.40	.75	.88
.95	1.00	.96	.39	.76	.87
.96	1.00	.96	.38	.77	.87
.96	1.00	.95	.37	.78	.86
.97	1.00	.95	.36	.80	.86
.98	1.00	.94	.36	.81	.85
.98	1.00	.93	.35	.82	.85
.99	1.00	.92	.35	.82	.84
.99	1.00	.91	.35	.83	.83
.99	1.00	.89	.34	.84	.82
1.00	1.00	.87	.44	.84	.81
1.00	1.00	.86	.46	.85	.80
1.00	1.00	.84	.47	.85	.79
1.00	1.00	.82	.48	.86	.78
1.00	1.00	.79	.50	.86	.77
1.00	1.00	.77	.52	.87	.76
1.00	1.00	.74	.53	.87	.75
1.00	1.00	.70	.55	.87	.74
1.00	1.00	.67	.56	.88	.73
1.00	1.00	.63	.58	.88	.72
1.00	1.00	.60	.60	.88	.70
	1.00		.61	.88	

$$\text{DRAIN}_n = -K\left(\frac{d\phi}{dhi} - 1\right) \qquad 4.42$$

where: DRAIN_n is the soil water flux (drainage) at the end of the day, n, (mm/day);

K is hydraulic conductivity (mm/day);

ϕ is soil water pressure head (m);

hi is the segment depth measured downwards positively (m).

In a uniform soil, the term $\frac{d\phi}{dhi}$ is negligible because very large changes in hydraulic conductivity occur for only small changes in soil water content (Davidson et al 1969). At a hydraulic gradient of unity in homogeneous soils, Black et al (1969) confirmed that drainage flow is equal to hydraulic conductivity, therefore,

$$\text{DRAIN}_n = K \qquad 4.43$$

it was also reasoned that the hydraulic conductivity, K, is a logarithmic function of soil moisture content, i.e.

$$\ln \text{DRAIN}_n = C_1 M_{n-1} + C_2 \qquad 4.44$$

where: C_1 and C_2 are constants representing soil type.
The upper and lower limit for the hydraulic conductivity, K_{Sat} and K_{fc} occur when the soil moisture content is at or exceeds saturation, M_{Sat} and at or near field capacity, M_{fc}. Thus the constants C_1 and C_2 can be related to K_{Sat}, M_{Sat}, K_{fc} and M_{fc} as below:

$$\text{DRAIN}_n = \left(K_{Sat} \frac{K_{Sat}}{K_{fc}}\right)^{(M_{n-1} - M_{Sat})/(M_{Sat} - M_{fc})} \qquad 4.45$$

Equation 4.45 was used to calculate the amount of water lost from the soil through drainage and was tested against the experimental results.

Run-off, RUN_n is calculated by means of the latest version of equation developed by Hartman et al (1960) and improved by Knisel et al (1969). The original equation was developed in imperial units for a soil segment of 3 ft (1500 mm). Adjustments were carried out for conversion factors and depth and the final equations are as follows:

$$RUN_n = (PR\,(PR - P_1))/(B + (PR - P_1)) \qquad 4.46$$

where: RUN_n is surface run-off at the end of day, n, from a 300 mm soil profile (mm/day);

PR is precipitation (mm/day);

P_1 is the rainfall before run-off begins (mm);

B is an empirical constant.

Both P_1 and B are functions of an antecedent soil moisture index proposed by Hartman et al (1960) as follows:

$$P_1 = 85.59 - 2.05\ ASM_n \qquad 4.47$$

where: ASM_n is antecedent soil moisture index at the end of day, n, which is the mm of water above permanent wilting point (PWP) and is calculated from soil moisture content at the end of day n-1

$$ASM_n = (M_{n-1} - PWP \times hi \times BD); \qquad 4.48$$

where: PWP is permanent wilting point (mm H_2O/300 mm);

hi is depth of soil profile (300 mm);

BD is bulk density of soil (g/cm^3);

M_{n-1} as defined before.

For the empirical constant B, three equations are used to describe its functional relation with the antecedent soil moisture index namely:

$$\text{for } ASM_n \leqslant 25 \text{ mm, } B = 1447.8 - 51\ ASM_n \qquad 4.49$$

$$\text{for } ASM_n \leqslant 38 \text{ mm, } B = 458.16 - 11.6\ ASM_n \qquad 4.50$$

$$\text{for } ASM_n > 38 \text{ mm, } B = 53.34 - 1.15\ ASM_n \qquad 4.51$$

Time available was calculated by using the soil moisture values calculated from the above model.

4.7 Calculating Timeliness Penalty

When an operation extends beyond the desirable finishing week (WKD), a timeliness penalty occurs and is calculated by means of equations introduced by Link (1967) and further developed by Abo el ees (1978). The timeliness cost is defined as the cost of farm product loss due to late completion of sowing or planting operation, i.e.

$$TC = (Y_{max} - Y_{ave}) \times AREA \times PRICE \qquad 4.52$$

where:

TC	=	timeliness cost (£);	(£)
Y_{max}	=	maximum crop yield for sowing or planting at optimum time t_o (Figure 4.1)	(t/ha)
Y_{ave}	=	average yield for sowing or planting over a period starting at t_1 and finishing at t_2.	(t/ha)
AREA	=	crop area	(ha)
PRICE	=	product value	(£/ta)

The average yield over the period $t_1 - t_2$ is calculated by integrating the yield function with respect to time, over the given period such that:

$$Y_{ave} = \frac{\int_{t_1}^{t_2} f(t)dt}{t_2 - t_1} \qquad 4.53$$

From the analysis of the available data, a quadratic equation was fitted to the yield/time data as follows:

$$Y = C_1t^2 + C_2t + C_3 \qquad 4.54$$

where: Y is the yield if the crop is sown at the time, t;
t is sowing date;
C_1, C_2 and C_3 are coefficients.

By substituting equation 4.54 with $f(t)$ in equation 4.53, solving the equation in terms of t_1, the predictive equation for the average yield Y_{ave}, becomes:

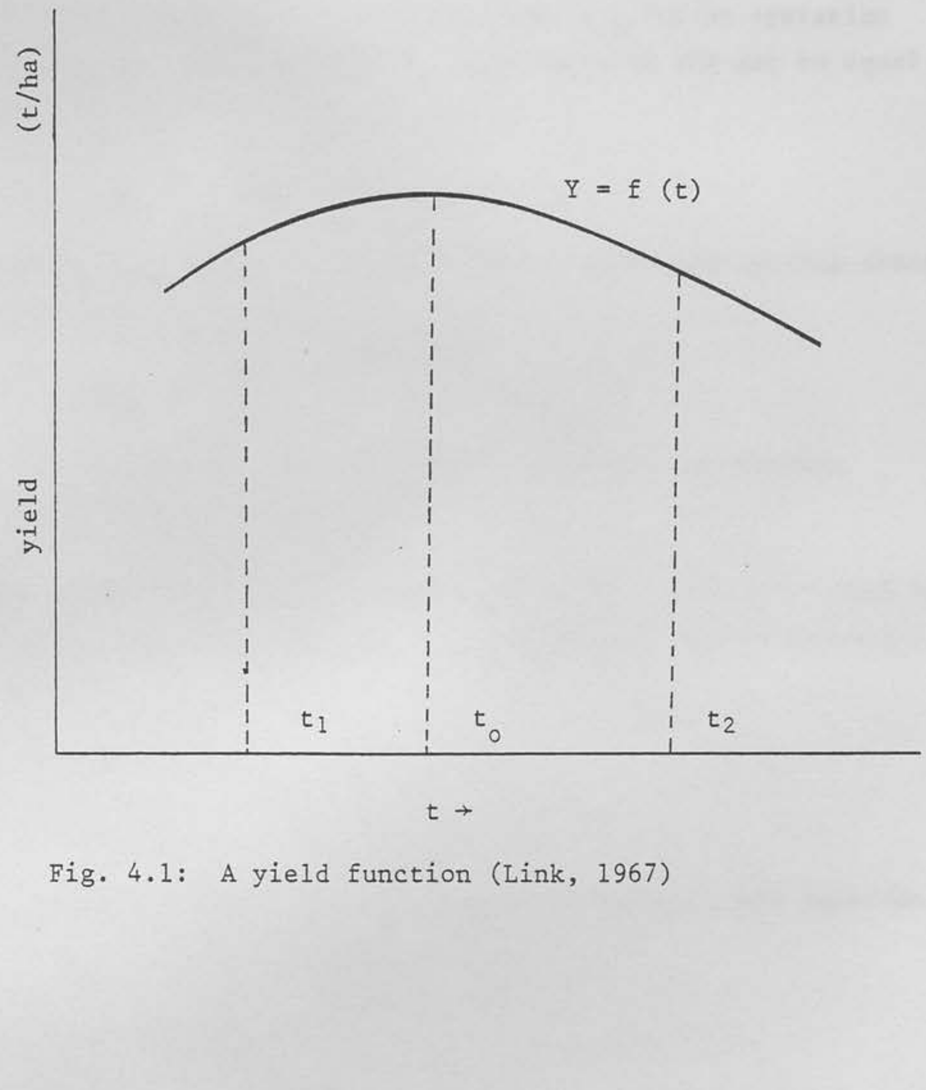

Fig. 4.1: A yield function (Link, 1967)

$$Y_{ave} = c_1.t_1^2 + DS.t_1 + QR \qquad 4.55$$

where: $$DS = c_1.LM + c_2 \qquad 4.56$$

$$QR = \frac{c_1}{3} LM^2 + \frac{c_2}{2} LM + C \qquad 4.57$$

$$LM = t_2 - t_1 \qquad 4.58$$

In order to obtain the optimum starting time, t_{os}, for an operation of a time span, LM, equation 4.56 is differentiated and set to equal to zero such that:

$$t_{os} = \frac{DS}{2c_1} \qquad 4.59$$

By substituting t_{os} instead of t_1 in equation 4.55, the optimum average yield is calculated such that:

$$Y_{oa} = QR - \frac{DS^2}{4c_1} \qquad 4.60$$

where: Y_{oa} is the optimum average yield for the optimum starting time, t_{os}.

The maximum yield time, t_o and maximum yield, Y_{max}, are calculated by differentiating the yield function 4.54 and setting the differential to equal to zero:

$$Y = 2c_1 t + c_2 = o \qquad 4.61$$

$$\therefore \quad t_o = t = -\frac{c_2}{2c_1} \qquad 4.62$$

Substituting for t in the equation 4.54 and rearranging the equation:

$$Y_{max} = -\frac{c_2^2}{4c_1} + c_3 \qquad 4.63$$

and the timeliness cost is:

$$TC = \left(-\frac{c_2^2}{4c_1} + c_3 - c_1 t_1^2 - DS\, t_1 - QR \right) \text{AREA PRICE} \qquad 4.64$$

By means of this equation and values for a, b, c, the starting week and time span of the operation, the timeliness cost of an operation for a given area is calculated.

4.8 Cost of Machinery

A costing routine, developed by Audsley and Wheeler (1978) at the N.I.A.E. utilising standard procedures suggested by the A.S.A.E., accounting for the effect of inflation and interest rate, and calculating the annual cost of machinery from the actual cash flow, is based upon the following equations:

$$PAC = \frac{(CAP + \sum_{n=1}^{N} REP_n FL^n - S_N FL^N)(FL - 1)}{FL(FL^N - 1)} \qquad 4.65$$

where:
PAC = present annual cost of machine;
CAP = initial capital;
S_N = current resale value of an N year old machine;
REP_n = current value of repair cost in the nth year;
N = number of years the machine is owned;
$FL = \frac{1 + gi}{1 + r}$;
gi = inflation rate;
r = interest rate.

The resale value of the machines is calculated by means of the standard method suggested by the A.S.A.E. as a percentage of new machine list price. A common form of equation is used to determine the resale value of four groups of machinery:

$$y = a_1 b_1^N \qquad 4.67$$

where: a_1 and b_1 are constants for a given group, and N, is the age of machine and y, is the resale value of an N year old machine as a percentage of the list price of the new machine.

Values of a_1 and b_1 for the different group, as derived from American and British data, are given in Table 4.3.

Repair cost also is calculated by using the A.S.A.E. standard procedures which are based on a study by Larson and Bowers (1954). The general form of the equation used is:

$$y = a_2 x^{b_2} \qquad 4.68$$

where: y is the total repair cost of machine, a_2 is constant depending on the type of machinery, x is accumulated hours of use as a percentage of wear-out life and b_2 is an exponent also depending on machine type.

According to this study, machinery is divided into four groups. The corresponding values of a_2 and b_2 for the repair cost equation, 4.68, is given in Table 4.4. Typical wear-out life resale groups and repair groups are given in Table 4.5.

The new list price used in these calculations which was originally an input data, is related to tractor power and plough width for tractors and ploughs, respectively. Using 1980 data, the tractor price equation is:

$$TPP = 115.34 \times POWER + 361.75 \qquad 4.69$$

where: TPP is tractor purchase price in £ sterling and POWER is tractor rated power in kW.

The coefficient of correlation for this analysis was 0.9005 and 81% of the data were explained by this equation within ± 5% confidence limits. Although slightly higher correlation coefficient 0.9006 was obtained for a quadratic equation, for simplicity, the linear equation is used for calculations. Data are presented in Figure 4.2.

The plough price equation, again using the 1980 data, is:

$$PPP = 396.99 \times NB - 167.86 \qquad 4.70$$

where: PPP = plough purchase price (£)
NB = number of plough bottoms.

The coefficient of correlation for this equation was 0.8992 and 80.86% of data were explained within ± 5% confidence limits. Different forms of equations were examined and the highest correlation 0.904 was obtained for a quadratic equation which was slightly higher than the one obtained for the linear form. Again, the linear equation is used for the calculations. Data are presented in Figure 4.3

TABLE 4.3 Values of a_1 and b_1 in equation 4.67 for different resale groups.

Group	a_1	b_1
1	68	0.920
2	64	0.885
3	60	0.885
4	56	0.885
*5	78.2	0.825
*6	97.0	0.821
*7	79.9	0.821

* derived from British data

TABLE 4.4 Values of a_2 and b_2 in equation 4.68 for different repair groups.

Group	a_2	b_2
1	0.100	1.5
2	0.120	1.5
3	0.096	1.4
4	0.0127	1.4
5	0.059	1.4
6	0.191	1.4
7	0.301	1.3

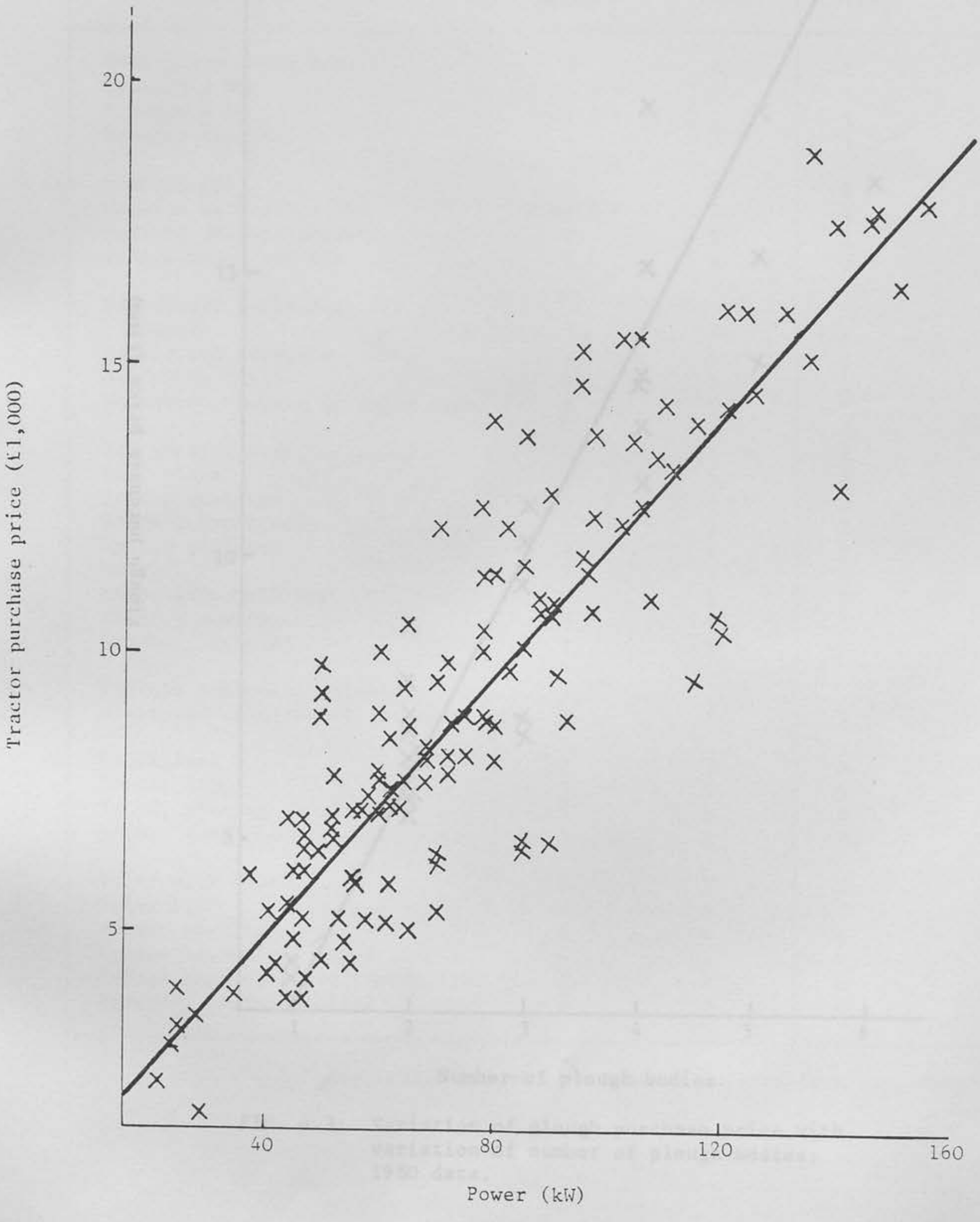

FIG. 4.2: Variation of tractor purchase price in relation to tractor rated power, 1980 data.

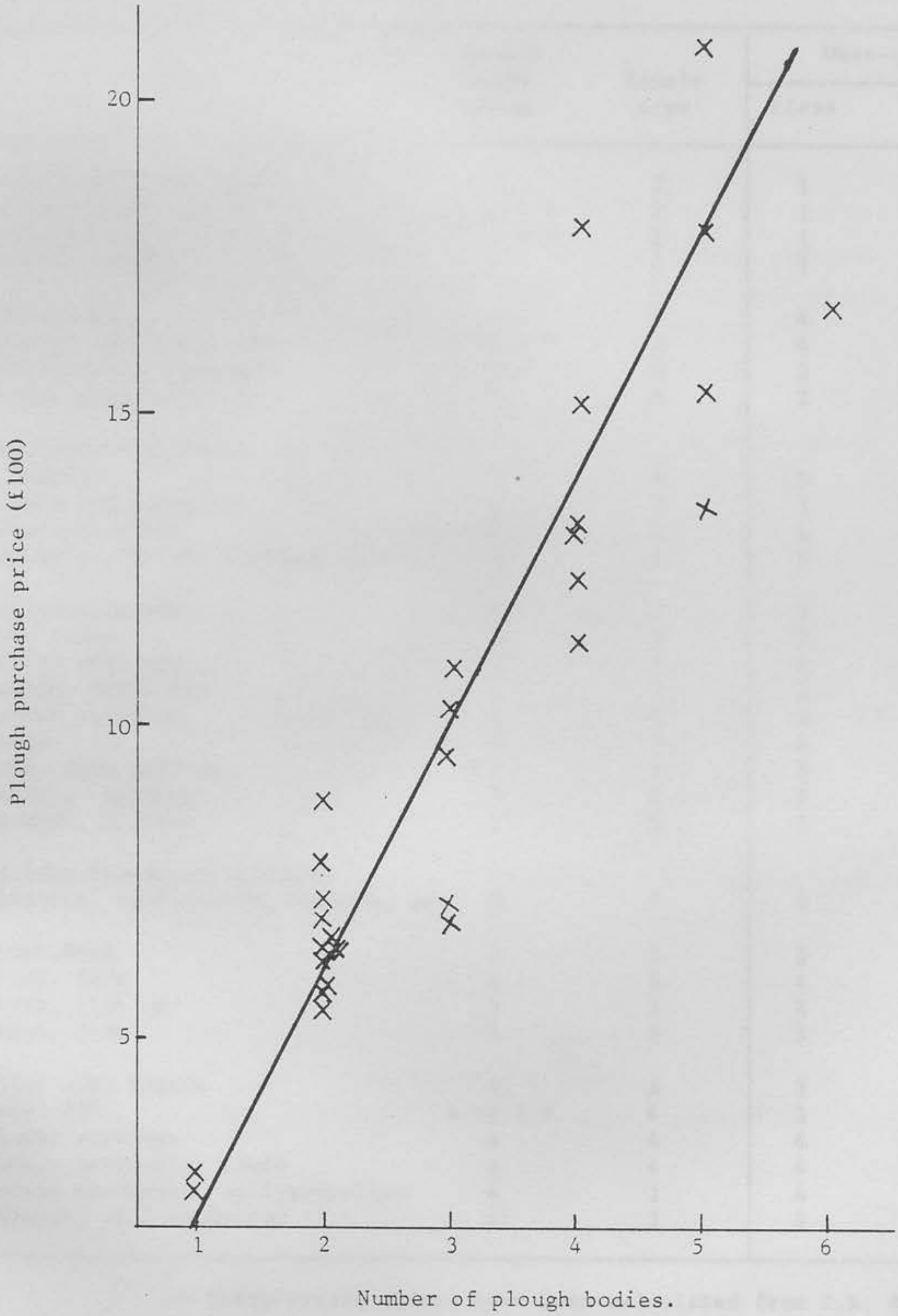

FIG. 4.3: Variation of plough purchase price with variation of number of plough bodies; 1980 data.

TABLE 4.5: List of machine types (Audsley and Wheeler, 1978)

Machine	Resale value group	Repair type	Wear-out life Class	Wear-out life Hours
Stationary power unit	1	2	1	12,000
Tractor 2 WD	1 or 5 *	2	1	12,000
Tractor 4 WD	1 or 5 *	1	1	12,000
Tractor crawler	1	1	1	12,000
Combine PTO	2	5	4	2000
Combine self-propelled	2 or 6 *	3	4	2000
Swather self-propelled	2	5	2	2500
Forage wagon and box	2	5	2	5000
Fertilizer equipment, dry or liquid	3	6	5	1200
Floats and scrapers	3	3	3	2500
Harvester flail	3	4	4	2000
Harvester, potato or sugar beet	3	4	3	2500
Hay conditioner	3	5	3	2500
Land plane	3	3	3	2500
Loader ensilage	3	5	4	2000
Loader, front end	3	3	3	2500
Manure spreader	3	3	3	2500
Mower	3	7	4	2000
Rake, side delivery	3	5	3	2500
Seeding equipment	3	5	5	1200
Sprayer, mounted	3	5	5	1200
Tillage equipment, ploughs, planters, cultivators, harrows, etc.	3	7	3	2500
Truck, feed	3	3	3	2500
Truck, farm	3	4	4	2000
Truck, pick up	3	3	4	2000
Wagon, feed	3	5	3	2500
Baler with engine	4	3	3	2500
Baler PTO	4 or 7 *	4	3	2500
Blower ensilage	4	4	4	2000
Forage harvester, towed	4	4	4	2000
Forage harvester, self-propelled	4	3	4	2000
Sprayer, self-propelled	4	3	4	2000

* These resale values have been calculated from U.K. data

In addition to these costs, labour and fuel costs also are calculated. The cost of labour for tillage operations is assumed to be that portion of the operator's wage paid for the time which is spent for tillage operations.

$$LCOST = \frac{LYCT \times HOURS}{THOUR} \qquad 4.71$$

where: LCOST is labour cost for ploughing (£), HOURS is the time spent for ploughing (hours), LYCT total yearly wage of the operator (£) and THOUR is the total hours of tractor utilisation for whole farm.

According to Cottrell and Audsley (1976) the fuel cost is related to the work rate of the tractor and fuel energy content such that:

$$TFCOST = \left(\frac{UFCOST \times POWER}{PAFC}\right) \times AREA \qquad 4.72$$

where: TFCOST = total fuel cost for ploughing (£);
AREA = area ploughed (ha);
UFCOST = unit cost of fuel (£/l);
u = tractor fuel energy content (kwh/l);
PAFC = plough work rate (ha/h);
POWER = as defined before.

Present annual cost of plough was calculated by using equation 4.65 and used in the calculation of the total cost of the system.

$$TCOST = PAC + PLPAC + TC + LCOST + TFCOST$$

where: TCOST = total cost of the system;
PLPAC = present annual cost of plough;
PAC, TC, LCOST and TFCOST are as previously defined.

5. EXPERIMENTAL WORK

5.1 Plough Draught Experiment

The objectives of the experiment on Scottish soils were firstly, to confirm the validity of the plough draught equation 4.18, and secondly, to obtain more data for the empirical determination of cone index from soil moisture content and density equation 4.9.

5.1.1 Equipment

The tractor used in this experiment was a Massey-Ferguson 575 developing 48.5 kW (66 hp) at an engine speed of 2000 rev/min. The four wheel drive tractor weighs 2.824 kg (6225 lb) including fuel, oil and water and was fitted with 13.6/12-36 and 6-19 tyres at the rear and front, respectively. Tyre pressures were adjusted to meet the manufacturer's recommendations, i.e. 179 kN/m^2 (26 psi) and 83 kN/m^2 (12 psi) for the front and rear tyres, respectively. A free rotating fifth wheel was mounted at the rear end of the plough frame to record actual speed, (plate 5.1).

A three point linkage dynamometer was used to measure draught force of the plough. This dynamometer which measures both horizontal and vertical forces with three strain-gauged beams was developed by Scholtz (1964, 1966), (plate 5.2).

In order to obtain the mains power required for the oscillograph, a Honda, EC 1500 mains generator was used. This generator is run by a 1.5 kW four stroke petrol engine and produces a 240 V alternating current. The lightweight (20 kg) unit was mounted on the front of a Land-Rover, (plate 5.3).

Two small, direct current, tacho-generators were also used. One of them was mounted on the fifth wheel and the other one on the rear tractor wheels to produce a direct current voltage proportional to the speed of each tyre in order to measure wheel slip (plate 5.4).

A four wheel drive Land-Rover was used as a mobile laboratory, containing the recording equipment as well as carrying the generator (plate 5.3).

Plate 5.1: The plough draught experiment in progress.

Plate 5.2: Three point linkage dynamometer.

Mains generator.

Plate 5.3: The mains generator mounted on the mobile laboratory.

Tachometer generator on tractor.

Tachometer generator on depth wheel.

Plate 5.4: Arrangement of the "Tachometer Generators".

A Bell and Howell type 5-137 oscillograph which uses type 7-300 galvanometers was used to record the output current produced by the two strain gauge bridges on the dynamometer and by the two tacho-generators. These galvanometers are electromechanical transducers which accept electrical energy and transform it into a mechanical rotation. This rotation is measured by directing a light beam by means of a mirror to a photo-sensitive paper (plate 5.5).

A Massey-Ferguson MF-34 reversible 3 furrow plough was used with 3, YS bodies and share points on one side and 3, HS base bodies on the other side. The tail angles at the end of mouldboards were 0.62 and 0.90 rad.for YS and HS bases, respectively. The YS bodies were originally fitted with sword landsides but, after few runs the swords were burnt off and, eventually, swords were fitted on both types of plough bodies (plate 5.6).

A Bush recording soil penetrometer (Anderson et al. 1980) which was developed at the SIAE and manufactured by Findlay Irvine Limited, was used in this study. This instrument is an electronic hand-held cone penetrometer in which the applied force to drive the cone into the soil is measured by a robust strain gauged transducer and fed into a digital readout. These readings can also be directed into a programmable calculator and stored. By means of this penetrometer, readings can be obtained in any intervals up to 500 mm depth (plate 5.7).

A hand-held gamma-ray transmission system was used to measure soil bulk density in situ (Soane et al. 1971b). This equipment was developed and tested at the SIAE and compared with conventional gamma-ray transmission equipment. The advantage of this instrument over conventional ones is its ability to record accurate results for very near surface profiles (30 mm below the surface) and more detailed readings for other parts of the profile (plate 5.8).

5.1.2 Sites

Originally six fields on Bush Estate, Midlothian, Scotland, were chosen in order to obtain a sufficient range of soil types, surface cover and compaction levels, but, one of the sites at Roslin had to be discarded due to permanent ponding which created trafficability problems.

Plate 5.5: The Oscillograph.

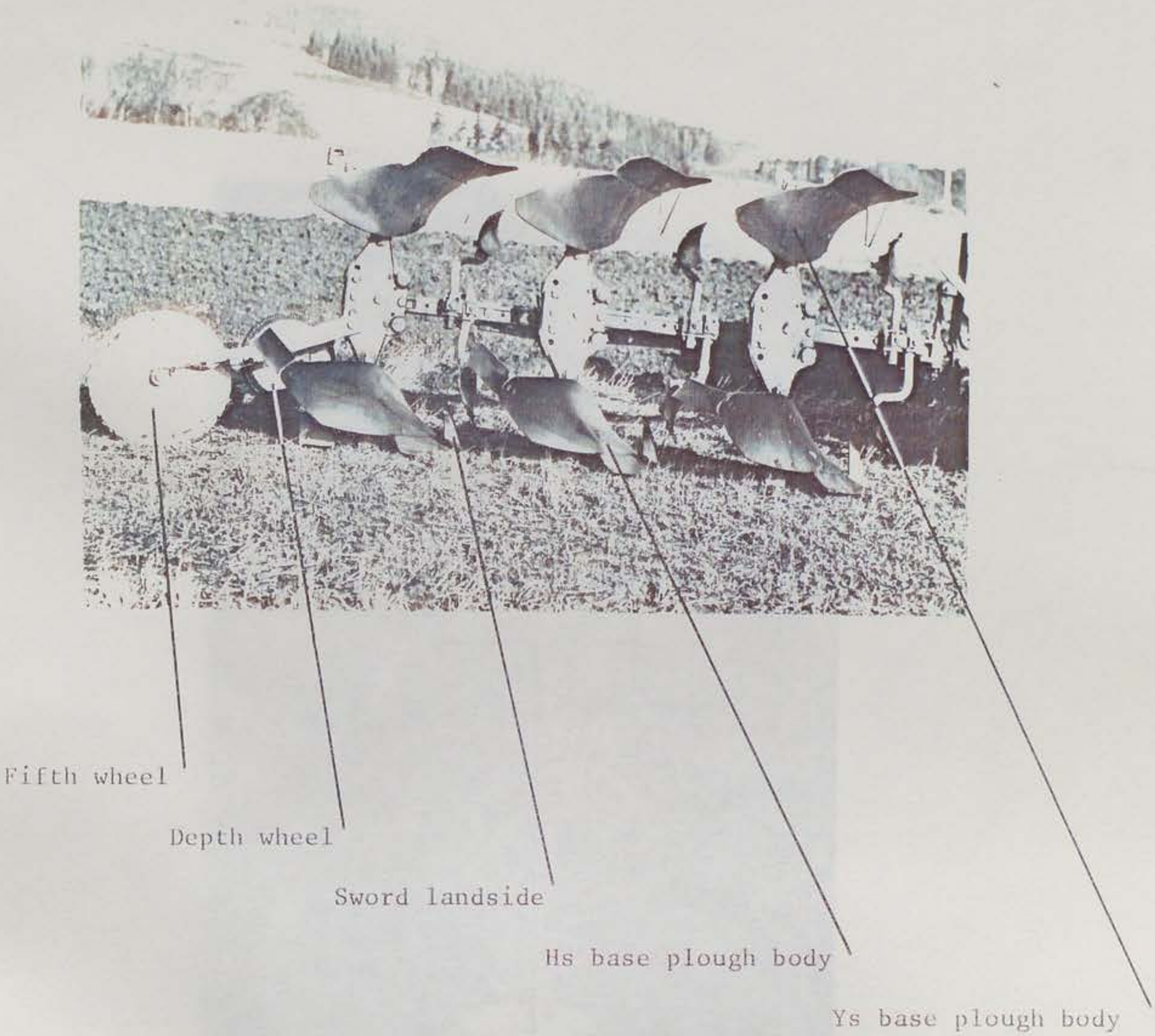

Plate 5.6: Plough frame with alternative plough bodies,
sword landside, fifth wheel and depth wheel.

Plate 5.7: A "Bush Recording Penetrometer".

Plate 5.8: Hand held "Gamma-ray Transmission Equipment", used to measure *in situ* soil bulk density.

(S.I.A.E. photograph)

TABLE 5.1: Site names and specifications.

No	Name	Initials	Soil Cover	Crop	Topography
1	Section 7	S7	Stubble	Barley	Flat
2	Fulford Camp	FC	Bare	Potato	Slope 10%
3	Lower Fulford	LF	Stubble	Barley	Slope 10%
4	Smith's Holding	SH	Stubble	Barley	Flat
5	House of Muir	HM	Bare	Potato	Slope 10%
6	Roslin	RN	Bare	Potato	Slope 10%

The two different surfaces, stubble and bare soil enhanced the range of soil densities in the experiment. The stubble was after barley on a fairly compacted soil. The bare soil after potatoes was very loose and contained a high percentage of air filled pores. The names of the fields, surface cover, initials used and their topography are given in Table 5.1.

5.1.3 Soils

Soil types varied from very poorly drained to freely drained soils. The chosen soil series (Darvel, Alluvium, Easter Bush and Biel) fell into three drainage categories of freely, moderately and poorly drained (Table 5.2).

TABLE 5.2 Soil types and their drainage categories.

FIELD	NAME	SOIL TYPE (SERIES)	ASSOCIATION	DRAINAGE CATEGORY	USDA TEXTURE
1	S7	DARVEL	DARVEL	FREE	SL
2	FC	ALLUVIUM	UNDIFFERENTIATED	FREE	SL
3	LF	BIEL	BIEL	POOR	CL
4	SH	EASTER BUSH	DARVEL	MODERATE	SL
5	HM	BIEL	BIEL	POOR	CL

Darvel series are freely drained brown forest soils. In top 280 mm, the texture is sandy loam with weak medium crumb, very friable, a low organic matter content, small rounded stones and abundant roots. The surface horizon of this soil is generally less than 300 mm, but, occasionally, organic matter has been noted up to a depth of 510-610 mm.

Alluvium is a dark brown sandy loam with a moderate organic matter content, a weak moderate sub-angular blocky structure and occasional small sub-angular stones. This gradually changes into a brown sandy loam sub-soil, freely drained.

Biel is a reddish brown clay loam with a coarse blocky structure, plastic texture, low organic matter content, occasional stones, frequent roots and a sharp change into a reddish brown clay, coarsely prismatic sub-soil. The main feature of this soil is its uniform colour throughout its extent.

Easter Bush is a dark sandy loam with a very weak structure, moderate organic matter content, occasional small stones, abundant roots and a sharp change into a pale coarse sandy loam to loamy fine sand. This soil is developed on a fluvio-glacial sand similar to Darvel. Full descriptions of these soils have been published by Soil Survey of Scotland (Ragg and Futty, 1967).

5.1.4 Layout

An area of 100 m x 150 m was chosen on each site and sub-divided into two smaller plots of 50 m x 150 m. The following independent variables are set in order to achieve enough variation:

a) five common Scottish soils ranging from sandy loam to clay loam (Table 5.2);

b) three different drainage groups of free, imperfect and poor drainage (Table 5.2);

c) two different levels of compaction (densities);

d) two different soil surface conditions;

e) 3-4 soil moisture levels;

f) three different ploughing speeds of slow, medium and fast ($\geqslant 2$, > 4 and > 6 km/h);

g) two different mouldboard tail angles (0.62 and 0.90 radians);

h) sword landside fitted or removed.

Three dependent variables also were measured as follows:

i) cone index;

ii) plough draught;

iii) wheel slip.

To restrict the number of variables in the experiment, a number of parameters were kept constant, or almost constant, namely:

a) tyre size;

b) load on tyre (tractor weight);

c) tyre pressure;

d) tractor size;

e) number of plough bodies;

f) depth of cut;

g) width of cut.

5.1.5 DEFINITIONS

Before discussing the procedure it is appropriate to define the codes and abbreviations which will be referred to in this section.

Field Number, FN, is a number chosen arbitrarily in order to identify each site (Table 5.1) and varies from 1-5.

Field names, FNA, are abbreviations of field names used in addition to field number for identification.

Plough number, PL, is used to identify the type of plough which is used: PL = 1 is the plough with a tail angle of 0.90 radian and PL = 2 is the plough with a tail angle of 0.62 radian.

Run no, RUN, is an identification used for each run of which two were made for every plough number.

Speed, SP, is an identification used to specify the travel speed. The three letters of S, M and F are used to refer to slow ($>$ 2 km/h), medium ($>$ 4 km/h) and fast ($>$ 6 km/h), respectively.

Day no, DY, is used to identify the number of the day during which the run was carried out starting with the first set of runs carried out on day one, the second set of runs on day two and so on. This number also identifies the level of soil moisture content. Up to three day numbers were used with one exception when a fourth day was required.

Record no, RN. The output from the oscillograph was numbered from 1-210 for every run, plough, speed, day and field number.

Sword conditions, SD. SD = 1 refers to the plough with sword landside and SD = 0 to the one without it.

5.1.6 Measurements

Soil bulk density, BD, was measured by means of the gamma-ray densiometer at the start of the experiment. Ten readings were taken for each site, the first one at a depth of 60 mm and the rest at increments of 30 mm up to a depth of 330 mm to represent the plough layer. The value of the bulk density at the depth of 180 mm was found to be equal to the overall average throughout the profile of 330 mm depth.

Soil moisture content, MC, was measured by using the gravimetric technique. Five samples of 40 grams were taken for each day and dried for 20 hours at a temperature of 180°C. The moisture content was expressed in terms of grams of water in 100 grams of dry soil.

Cone index, was measured for each field on every day of the experiment by means of the NIAE recording penetrometer with a 60° cone of 322 mm^2 basal area. Ten series of readings were taken, each series containing ten readings from ten different depths, starting from 30 mm and increasing up to 300 mm with incrrments of 30 mm. These data were averaged for all depths CI1 and for the depth 150 mm, CI2.

Horizontal, HORZ, and vertical, VERT, forces, actual WS2 and rear wheel WS speed were continuously recorded during each experiment over a distance of 30 m for each speed. The galvanometers on the oscillograph were set to zero when the plough was stationary on a flat level surface.

Calibration of the force transducers were carried out prior to the start of the experiment. The calibration figures are given in Appendices A.1. - A.3. The oscillograph was then calibrated according to these figures as follows:

Zero points were at the centre and one centimeter above the first bottom line of the graph paper for the curves of vertical and horizontal, fifth wheel and tractor wheel, respectively. Each cm on the graph from the zero point represents one kN for vertical curve, 2 kN for horizontal and 0.2 m/s for fifth wheel and tractor wheel curves. An example output from the oscillograph is presented in Figure 5.1.

5.1.7 Results

Bulk Density

Soil bulk density increased with depth of the soil profile for sites with bare soils. On sites with stubble cover, bulk density decreased with depth up to around 180 mm after which the bulk density started increasing and reached a maximum at the depth of 330 mm. Results and standard deviations from the mean and standard errors are shown in Table 5.3. Variation of bulk density with depth, soil type and surface cover are shown on Figure 5.2.

Cone Index

Values of the cone index for each depth were averaged and converted into kPa by a multiplication factor of 22 (a calibration factor). Table 5.4 shows these results along with the unconverted values for each depth at varying soil moisture contents for different fields. Corresponding soil moisture content for each day is also given in the same table. Cone index increased with the increasing depth and this trend was consistent for all soils and moisture levels. Figures 5.3 to 5.7 shows this trend and variation of cone index with soil moisture content.

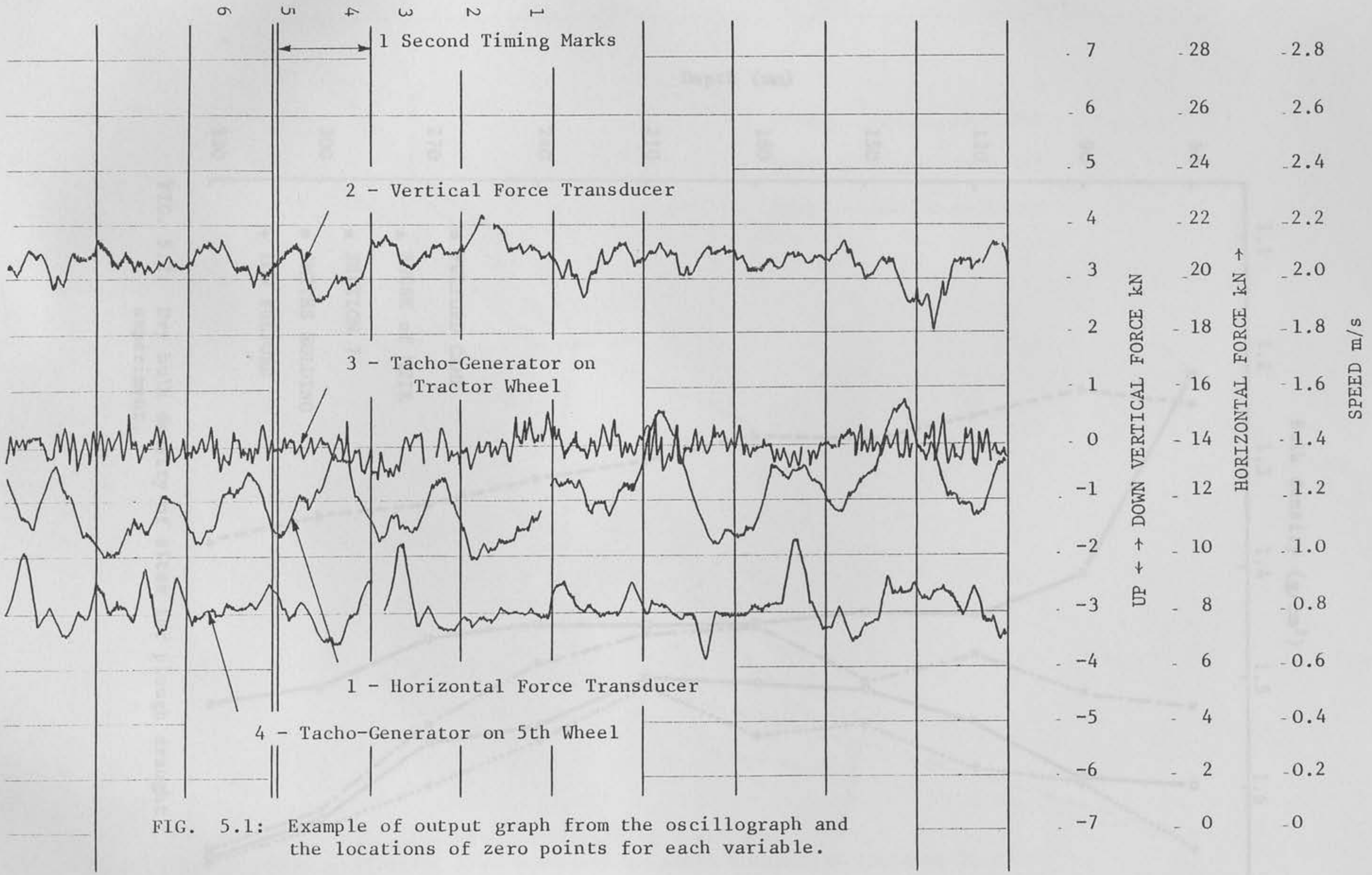

FIG. 5.1: Example of output graph from the oscillograph and the locations of zero points for each variable.

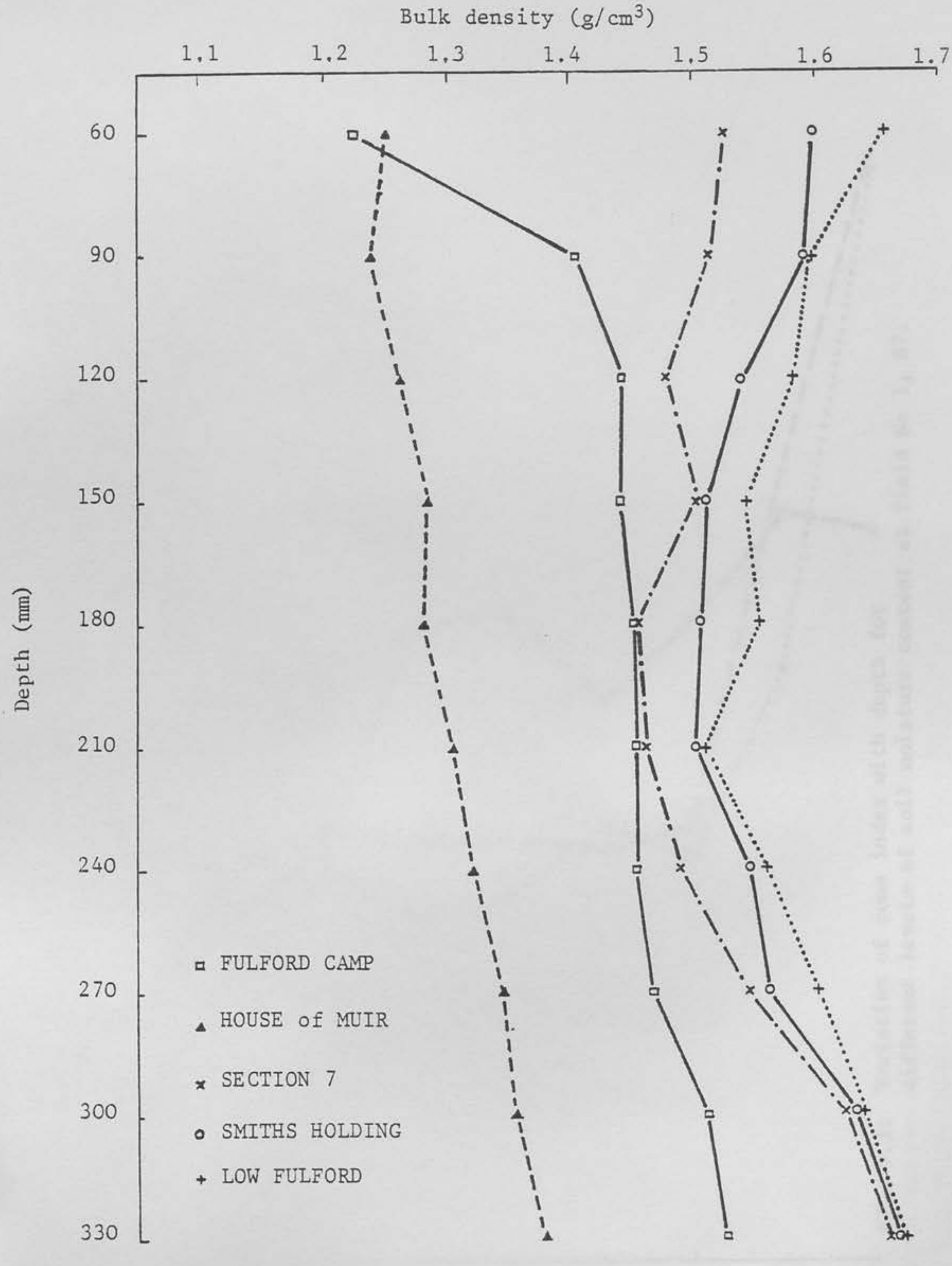

FIG. 5.2: Dry bulk density of sites for plough draught experiment.

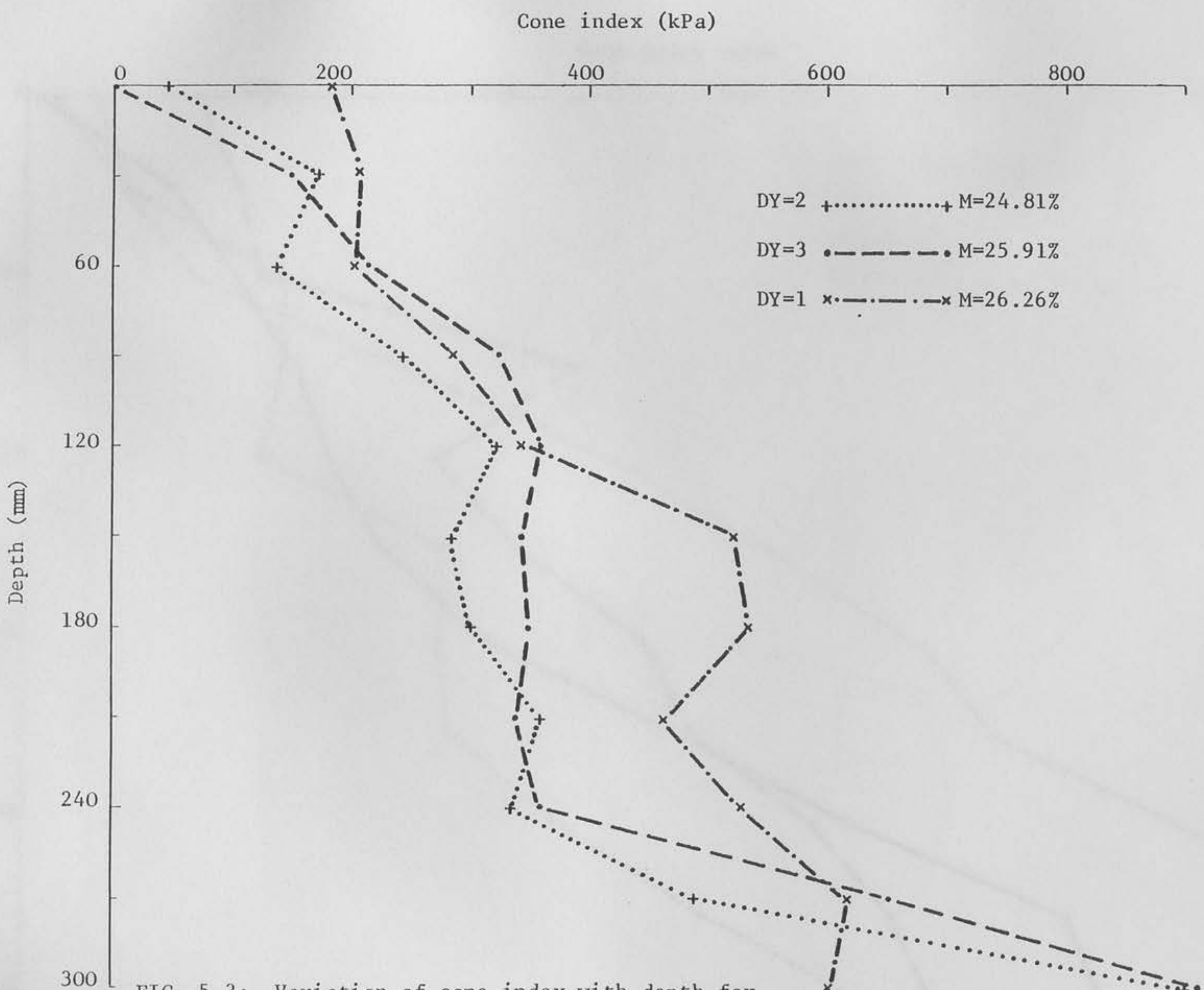

FIG. 5.3: Variation of cone index with depth for different levels of soil moisture content at field No 1, S7.

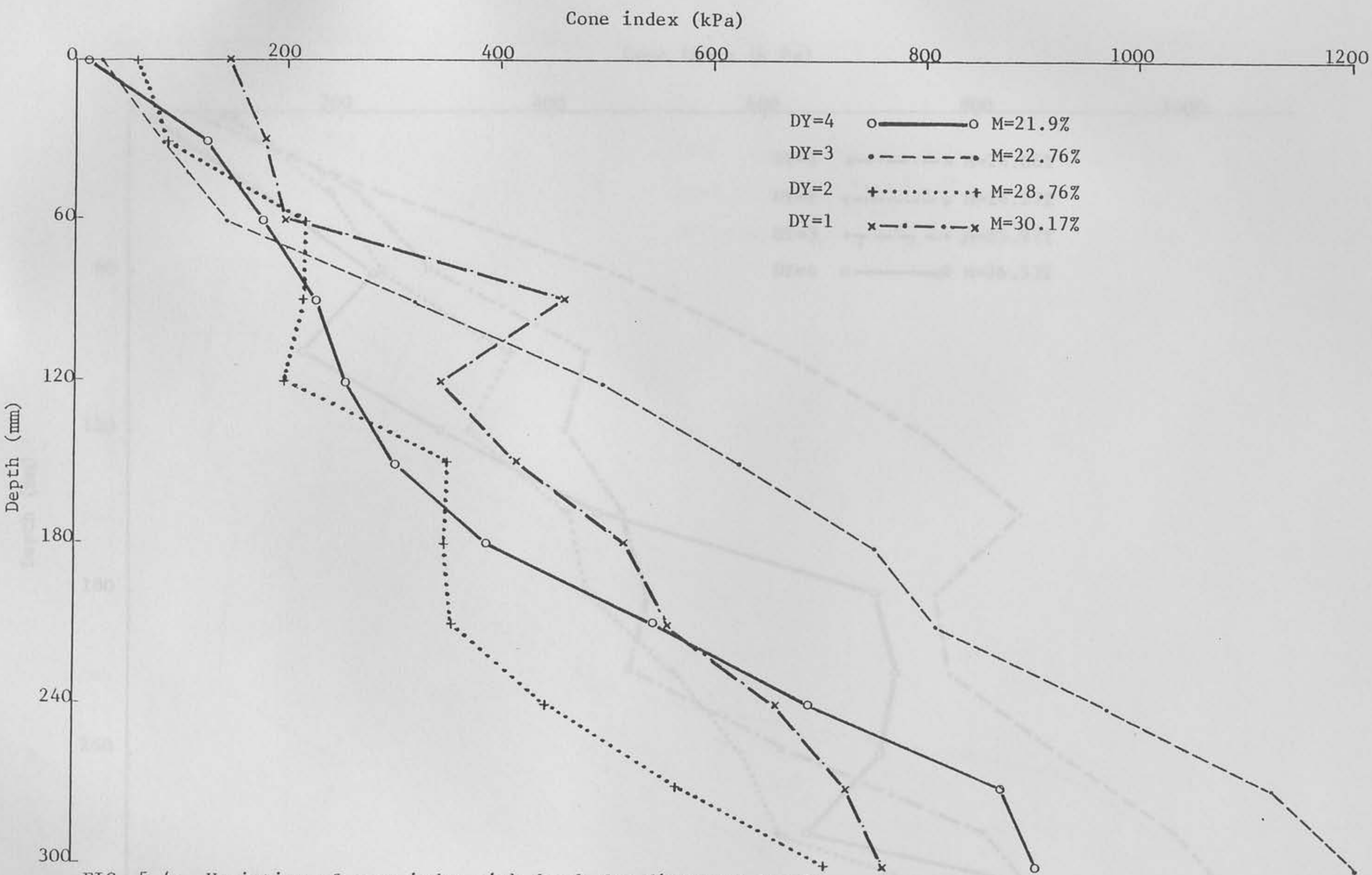

FIG. 5.4: Variation of cone index with depth for different levels of soil moisture content at field No 2, FC.

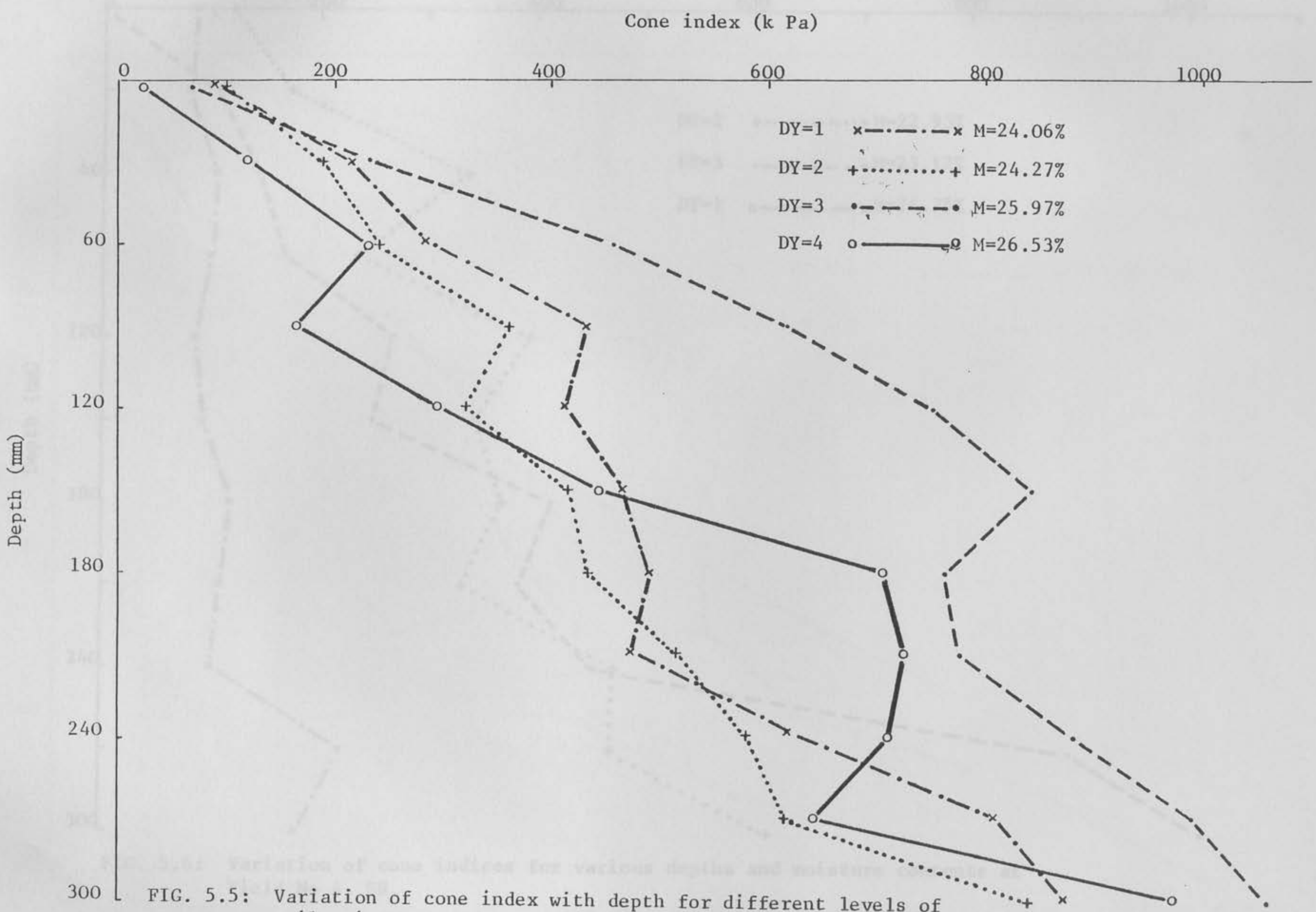

FIG. 5.5: Variation of cone index with depth for different levels of soil moisture content at field No 3, LF.

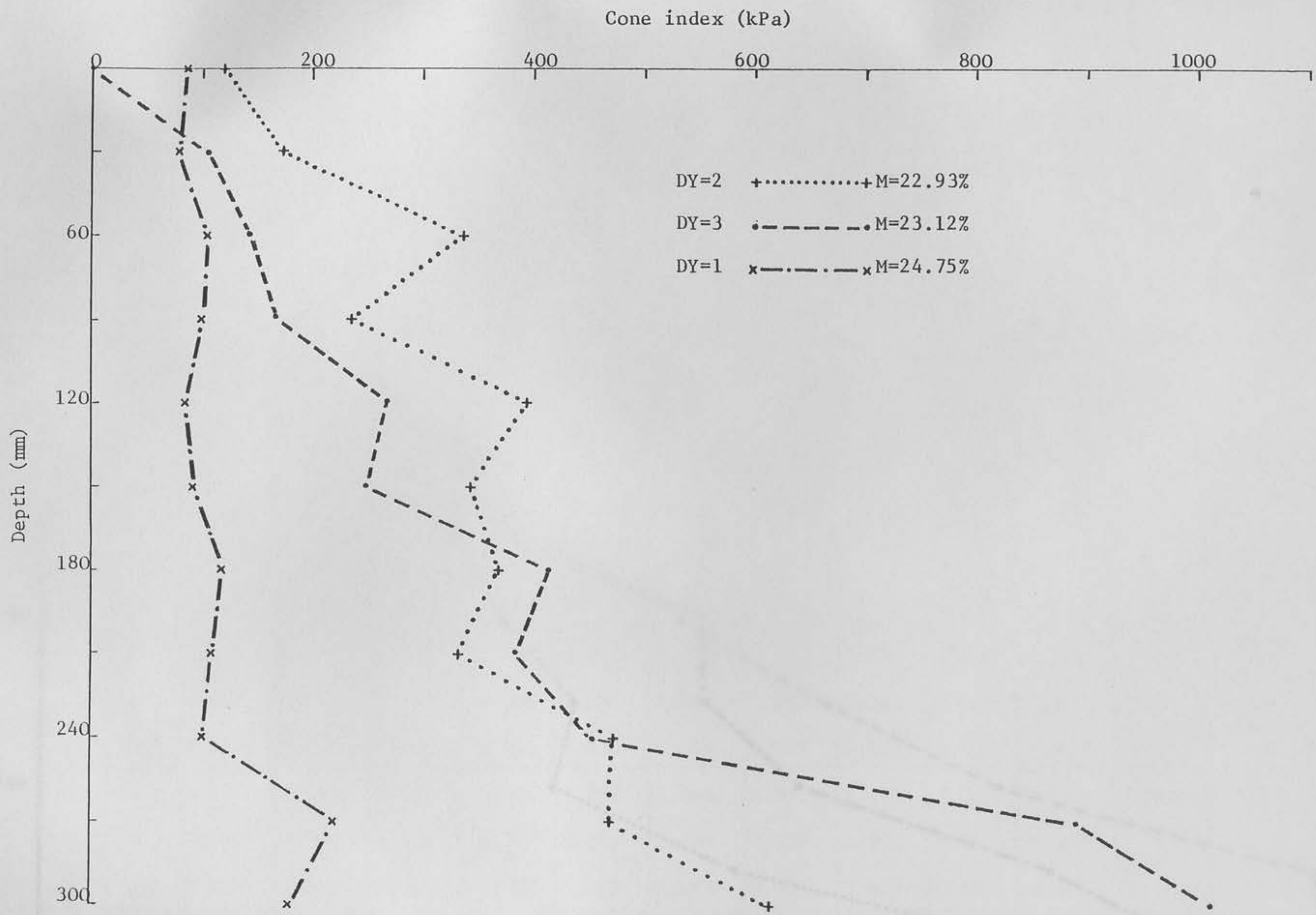

FIG. 5.6: Variation of cone indices for various depths and moisture contents at Field No 4, SH.

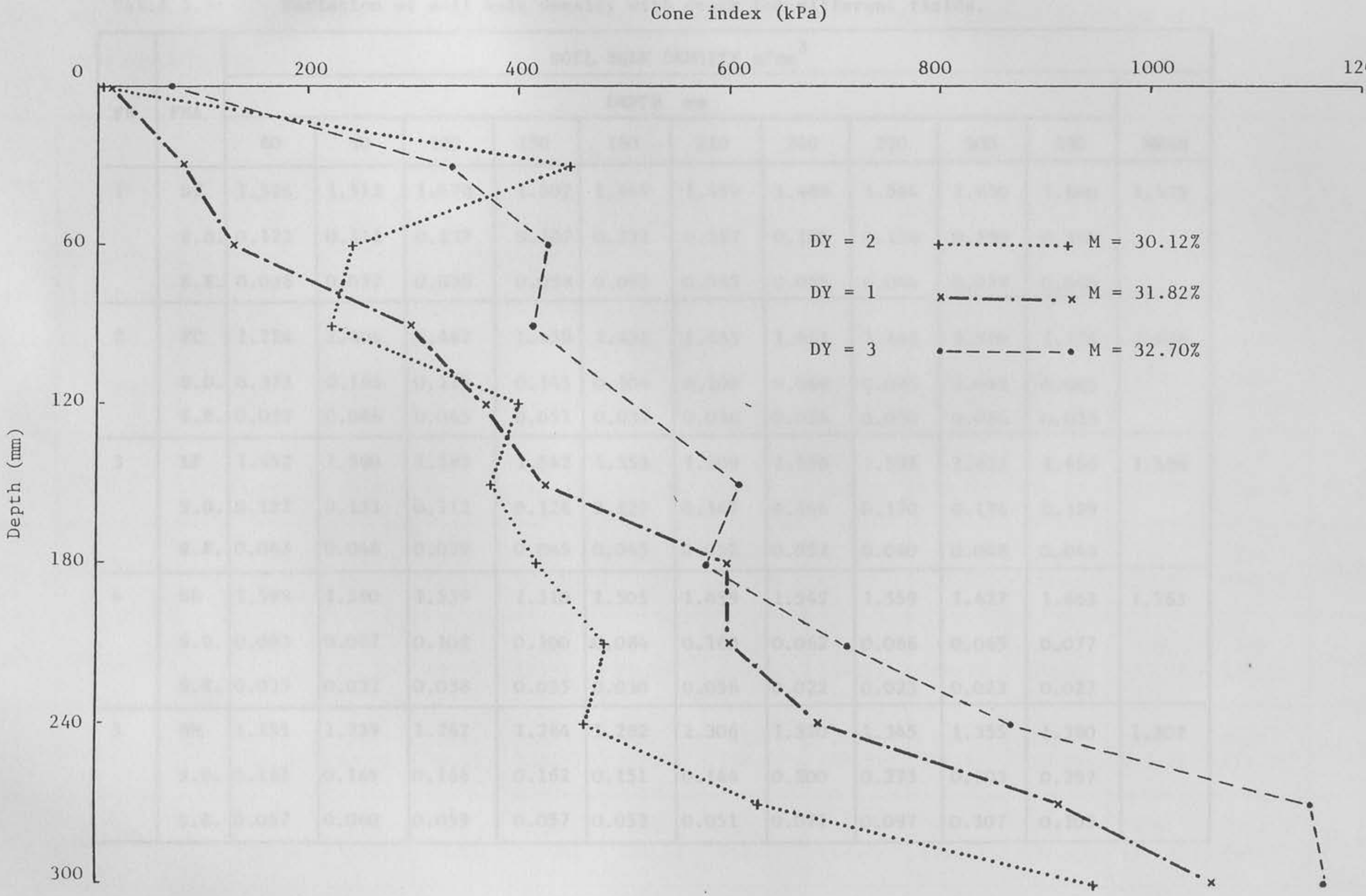

FIG. 5.7: Variation of cone indices for various depths and soil moisture content, field No. 5 House of Muir.

TABLE 5.3: Variation of soil bulk density with depth for different fields.

FN	FNA	SOIL BULK DENSITY g/cm^3										
		DEPTH mm										
		60	90	120	150	180	210	240	270	300	330	MEAN
1	S7	1.526	1.512	1.478	1.502	1.449	1.459	1.488	1.544	1.620	1.660	1.523
	S.D.	0.123	0.111	0.132	0.187	0.231	0.227	0.190	0.154	0.130	0.154	
	S.E.	0.036	0.032	0.038	0.058	0.067	0.065	0.055	0.044	0.038	0.045	
2	FC	1.224	1.404	1.442	L.439	1.452	1.453	1.451	1.466	1.510	1.525	1.436
	S.D.	0.373	0.186	0.126	0.145	0.104	0.100	0.069	0.085	0.045	0.045	
	S.E.	0.032	0.066	0.045	0.051	0.037	0.036	0.024	0.030	0.016	0.016	
3	LF	1.652	1.590	1.582	1.542	1.553	1.509	1.556	1.598	1.623	1.656	1.586
	S.D.	0.122	0.131	0.112	0.126	0.127	0.147	0.146	0.170	0.134	0.129	
	S.E.	0.043	0.046	0.039	0.045	0.045	0.052	0.052	0.060	0.048	0.046	
4	SH	1.599	1.590	1.539	1.510	1.505	1.499	1.542	1.559	1.627	1.663	1.563
	S.D.	0.093	0.087	0.108	0.100	0.084	0.160	0.062	0.066	0.065	0.077	
	S.E.	0.033	0.031	0.038	0.035	0.030	0.056	0.022	0.023	0.023	0.027	
5	HM	1.251	1.239	1.262	1.284	1.282	1.306	1.320	1.345	1.355	1.380	1.302
	S.D.	0.161	0.169	0.166	0.162	0.151	0.144	0.200	0.273	0.303	0.297	
	S.E.	0.057	0.060	0.059	0.057	0.053	0.051	0.071	0.097	0.107	0.105	

Table 5.4: Preliminary results of cone index for different depths and moisture contents at various fields on different days of the experiment.

FN	FNA	DATE	DY	CONE INDEX kPa (as read from the instrument) DEPTH mm											M %
				0	30	60	90	120	150	180	210	240	270	300	
1	S7	12/12/79	1	185 (8.4)	207 (9.4)	205 (9.3)	282 (12.8)	343 (15.6)	521 (23.7)	532 (24.2)	462 (21.0)	524 (23.8)	618 (21.1)	601 (27.3)	26.26
1	S7	14/1/80	2	46 (2.8)	172 (7.8)	134 (6.1)	246 (11.2)	321 (14.6)	286 (13.0)	301 (13.7)	361 (16.4)	332 (15.1)	488 (22.2)	906 (41.2)	24.81
1	S7	16/1/80	3	0 (0)	150 (6.8)	213 (9.7)	326 (14.8)	359 (16.3)	345 (15.7)	350 (15.9)	341 (15.5)	361 (16.4)	653 (27.9)	904 (41.1)	25.99
2	FC	12/12/79	1	147 (6.7)	178 (8.1)	198 (9.0)	462 (21.0)	343 (15.6)	415 (18.9)	519 (23.6)	561 (25.5)	660 (30.0)	728 (33.1)	763 (34.7)	30.17
2	FC	18/12/79	2	57 (2.6)	90 (4.1)	218 (9.9)	218 (9.9)	198 (9.0)	352 (16.0)	350 (15.9)	357 (16.3)	447 (20.3)	570 (25.9)	708 (32.3)	28.76
2	FC	14/1/80	3	20 (0.9)	84 (3.8)	143 (6.5)	319 (14.5)	497 (22.6)	625 (28.4)	755 (34.3)	812 (36.9)	975 (44.3)	1186 (53.9)	1210 (55.0)	22.76
2	FC	16/1/80	4	11 (0.5)	123 (5.6)	176 (8.0)	227 (10.3)	255 (11.6)	301 (13.7)	389 (17.7)	552 (25.1)	691 (31.4)	873 (39.7)	903 (44.7)	21.90

Table 5.4 (continued)

FN	FNA	DATE	DY	CONE INDEX kPa (as read from the instrument)											M %
				DEPTH mm											
				0	30	60	90	120	150	180	210	240	270	300	
3	LF	12/12/79	1	85 (3.9)	216 (9.7)	282 (12.8)	429 (19.5)	407 (18.5)	464 (21.1)	491 (22.3)	471 (21.4)	616 (28.0)	805 (36.6)	869 (39.5)	24.06
3	LF	18/12/79	2	95 (4.3)	189 (8.6)	240 (10.9)	361 (16.4)	319 (14.5)	414 (18.8)	433 (19.7)	517 (23.5)	578 (26.2)	612 (27.8)	838 (38.1)	24.27
3	LF	19/1/80	3	68 (3.1)	231 (10.5)	453 (20.6)	618 (28.1)	761 (34.6)	842 (38.3)	761 (34.6)	774 (35.2)	878 (39.9)	990 (45.0)	1061 (48.5)	25.97
3	LF	16/1/80	4	18 (0.8)	117 (5.3)	229 (10.4)	161 (7.3)	293 (13.3)	442 (20.1)	702 (31.9)	717 (32.6)	706 (32.1)	636 (28.9)	972 (44.2)	26.53
4	SH	13/12/79	1	88 (4.0)	81 (3.7)	106 (4.8)	101 (4.6)	84 (3.8)	90 (4.1)	117 (5.3)	106 (4.8)	101 (4.6)	218 (9.9)	178 (8.1)	24.75
4	SH	14/1/80	2	121 (5.5)	172 (7.8)	334 (15.2)	238 (10.8)	396 (18.0)	345 (15.7)	319 (14.5)	332 (15.1)	473 (21.5)	469 (21.3)	612 (27.8)	22.93
4	SH	16/1/80	3	0 (0)	108 (4.9)	145 (6.6)	167 (7.6)	268 (12.2)	249 (11.3)	414 (18.8)	385 (17.5)	455 (20.7)	893 (40.6)	1012 (46.0)	23.12

Table 5.4 (continued)

FN	FNA	DATE	DY	CONE INDEX kPa (as read from the instrument) DEPTH mm											M
				0	30	60	90	120	150	180	210	240	270	300	%
5	HM	15.1.80	1	13 (0.6)	81 (3.7)	132 (6.0)	297 (13.5)	372 (16.9)	427 (19.4)	601 (27.3)	601 (27.3)	684 (31.1)	917 (41.7)	1058 (48.1)	31.82
5	HM	15.1.80	2	4 (0.2)	453 (20.6)	242 (11.0)	222 10.1)	398 (18.1)	374 (17.0)	420 (19.1)	484 (22.0)	462 (21.0)	627 (28.5)	948 (43.1)	30.12
5	HM	24.1.80	3	68 (3.1)	338 (15.4)	429 (19.5)	414 (18.8)	407 (18.5)	618 (28.1)	581 (26.4)	715 (32.5)	869 (39.6)	1151 (52.3)	1164 (52.9)	32.70

Horizontal and vertical forces alongwith readings from the fifth wheel and the tractor drive wheel tacho-generators were converted into kN and m/s respectively. These results together with soil bulk density, moisture content and cone index values are given in Appendix B.1. Two values of cone index were chosen for comparison, first, the overall average for all depths and, second, the average value for the depth of 150 mm. Variations of these two means from each other was around ± 10%.

5.2 Cone Penetrometer Experiments

The objectives of the experiment are to investigate the type of the relationship between soil resistance to the penetration of a cone, soil moisture content and soil bulk density and to evaluate the coefficients of these relationships for varying soil types.

5.2.1 Equipment

The operating principles of the Military Engineering Experimental Establishment Soil Assessment Cone Penetrometer manufactured by Farnell and Company Limited, is based on the deflection of a calibrated compression spring under load. These deflections are read from a dial under a perspex window. Two different sizes of 60° cones with a base area of 322 mm^2 and 129 mm^2 can be used. Cones are fitted at the end of an extendable metal rod up to a length of 610 mm.

Bulk density sampling cones. Cylindric sampling cores were used to obtain a given volume of soil sample. Dimensions of the cores used are:

diameter - 39 mm
length - 19 mm
wall thickness - 1 mm
Total volume of the core - 22685.71 mm^3 (22.68 cm^3).

Soil moisture tins. Metal soil containers were used for the soil samples for moisture measurement.

5.2.2 Sites

Three sites around the Bush Estate in Midlothian, Scotland, were chosen. In each site a plot of 50 m x 10 m was identified and sub-divided into five smaller plots of 10 m x 10 m area. Table 5.5 indicates the names, surface cover and topography of the fields used.

TABLE 5.5 Site names, surface cover and topography.

FN	FNA	NAME	SURFACE COVER	TOPOGRAPHY
1	Pl H	PLOVER HALL	AFTER POTATO	FLAT
2	LG	LONG RIG	STUBBLE	FLAT
3	HF	HIGH FIELD	AFTER POTATO	FLAT

5.2.3 Soils

Three different soil types with three different drainage categories were chosen. These soils which cover most of the Scottish farms are Darvel, Macmerry and Winton Series. The Darvel series have been described in the previous section. The Macmerry Series, in the top 300 mm, are imperfectly drained dark brown sandy loams with a medium blocky friable structure, a moderate organic matter content, occasional stones, some rounded or sub-rouned and no mottles, clearly changing to a yellowish brown sandy loam sub-surface. The Winton Series, in the top 300 mm horizon, are poorly drained dark-grey brown sandy clay loams with a fine sub-angular blocky and friable structure, a moderate organic matter content, abundant roots, occasional stones and active worms. This horizon has a clear but irregular boundary and changes into a coarse blocky brown clay loam sub-surface (Table 5.6). Detailed information on the subsoils and the analytical data of these soils can be obtained from Ragg and Futty (1967).

TABLE 5.6 Soil type, associations, drainage category and USDA texture for different sites.

FN	FNA	SOIL TYPE	ASSOCIATION	DRAINAGE CLASS	USDA TEXTURE
1	P1 H	DARVEL	DARVEL	FREE	SL
2	LG	MACMERRY	WINTON	MODERATE	SL
3	HF	WINTON	WINTON	POOR	SCL

5.2.4 Procedure and Results

Four of the five smaller plots in each field was subjected to 4, 8, 12 and 16 additional wheel passes of the MF 575 tractor (as described in section 5.1.1) to provide a range of soil densities which were assessed by the cone sampling method. A depth of 150 mm was chosen to represent the plough layer and ten samples for each small plot were taken from this depth. Samples were weighed, dried at 180°C for twenty hours, weighed again and the bulk densities were calculated on a dry basis. In order to obtain a wide range of soil moisture contents, five soil samples were taken from each plot for moisture measurement at five day intervals. Soil moisture content was then calculated gravimetrically by subjecting the samples to twenty hours drying at the temperature of 180°C. Results were expressed in terms of grams of water in 100 grams of dry soil (dry basis).

The resistance to penetration of a 322 mm^2 base area cone was measured as an indication of soil strength. Measurements were taken at five intervals (as for soil moisture samples) for a depth of 150 mm as the cone indices at this depth proved to be a more reliable guide to soil strength throughout the whole profile of 300 mm (plough layer) than the mean of the cone index values measured at different depth intervals as in previous experiment. Fifteen readings were taken from each plot for this depth and averaged. Results were obtained in terms of lb/in^2 were converted into kPa. These results together with soil moisture and specific weight values for various fields and plots are shown on Tables 5.7 to 5.9.

TABLE 5.7: Soil moisture content and specific weight with measured values of cone index for Darvel soil at Ploverhall.

Plot No	Ref.	Soil moisture contents (% w/w)	Soil specific weight (kN/m^3)	Cone index (MPa)
1	1	27.55	12.25	0.558
1	2	26.11	12.25	0.683
1	3	33.04	12.25	0.517
1	4	36.52	12.25	0.524
2	5	34.45	12.24	0.531
2	6	30.76	12.24	0.586
2	7	28.87	12.24	0.869
2	8	25.19	12.24	0.779
3	9	27.09	12.25	0.807
3	10	25.07	12.25	0.889
3	11	31.07	12.25	0.586
3	12	33.95	12.25	0.572
4	13	34.14	12.29	0.565
4	14	30.71	12.29	0.676
4	15	24.16	12.29	0.978
4	16	26.31	12.29	0.862
5	17	25.58	12.27	0.827
5	18	25.66	12.27	0.1000
5	19	32.26	12.27	0.793
5	20	35.51	12.27	0.676

TABLE 5.8: Soil moisture content and specific weight with measured values of cone index for Macmerry soil at Longrig.

Plot No.	Ref.	Soil moisture contents (% w/w)	Soil specific weight (kN/m^3)	Cone Index (MPa)
1	1	24.60	12.93	1.061
1	2	28.50	12.93	0.730
1	3	25.10	12.93	0.910
1	4	29.22	12.93	0.834
1	5	23.09	12.93	0.868
2	6	26.80	12.80	1.165
2	7	28.80	12.80	0.751
2	8	24.17	12.80	1.034
2	9	30.27	12.80	0.848
2	10	28.63	12.80	0.965
3	11	26.05	12.91	1.199
3	12	30.30	12.91	0.730
3	13	26.75	12.91	1.061
3	14	26.05	12.91	0.882
3	15	31.26	12.91	0.841
4	16	26.65	12.44	1.116
4	17	29.00	12.44	0.827
4	18	27.20	12.44	1.041
4	19	27.86	12.44	0.889
4	20	28.82	12.54	0.854
4	21	27.30	12.54	0.985
4	22	29.80	12.54	0.813
4	23	25.00	12.54	0.965
4	24	28.45	12.54	0.972
4	25	29.13	12.54	0.854

TABLE 5.9: Soil moisture content and specific weight with measured values of cone index for Winton soil at High Field.

Plot No.	Ref.	Soil moisture content (% w/w)	Soil specific weight (kN/m^3)	Cone Index (MPa)
1	1	27.55	12.19	0.655
1	2	28.99	12.19	0.607
1	3	33.12	12.19	0.407
1	4	41.40	12.19	0.351
2	5	34.51	11.79	0.572
2	6	29.66	11.79	0.710
2	7	31.90	11.79	0.627
2	8	38.93	11.79	0.489
3	9	40.96	11.67	0.537
3	10	31.18	11.67	0.634
3	11	31.31	11.67	0.765
3	12	35.28	11.67	0.599
4	13	34.04	12.43	0.641
4	14	29.57	12.43	0.731
4	15	29.94	12.43	0.669
4	16	38.22	12.43	0.545
5	17	42.29	12.15	0.579
5	18	32.46	12.15	0.703
5	19	29.06	12.15	0.772
5	20	32.06	12.15	0.703

Figures 5.8 to 5.10 shows the variation of cone index values with changes in soil moisture content for different soil types. These measurements were taken in the Autumn of 1979. All the data is combined with the results obtained by Woorhees and Walker (1977) and are presented in Figure 5.11.

5.3 Measurement of Soil Tension

The objectives of the investigation were to obtain adequate soil moisture data in order to test the soil moisture prediction model and to examine the effect of vegetation on soil moisture status.

5.3.1 Equipment

Four, six cell tensiometers developed by Webster (1965) were used to measure soil moisture tension on different fields. The instrument is based on a device by Hack (1957) which in essence consists of a fine porous ceramic pot connected by a tube to a manometer or vacuum gauge (plate 5.9). The porous pot is placed in intimate contact with the soil and the whole instrument is filled with water so that the water passes through the pot until the suction on the manometer is in equilibrium with the suction on the soil. As the measurement of very low tension values were intended, a mercury manometer was used because of their greater accuracy in that range.

5.3.2 Sites

Two sites at Langhill farm, Midlothian, were selected. An area of 6m x 4m on permanent grass was fenced and divided into two smaller plots of 3m x 4m at each site. One of these small plots at each site was treated with Paraquat in order to obtain a bare soil surface. In the remaining plot, grass was cut to a height of 30 cm. Although the fields were sloping, a flat area was chosen so that no ponding would occur with rainfall of average intensity.

5.3.3. Soils

The sites were located on Macmerry and Winton soil series which are moderately and freely draining, respectively.

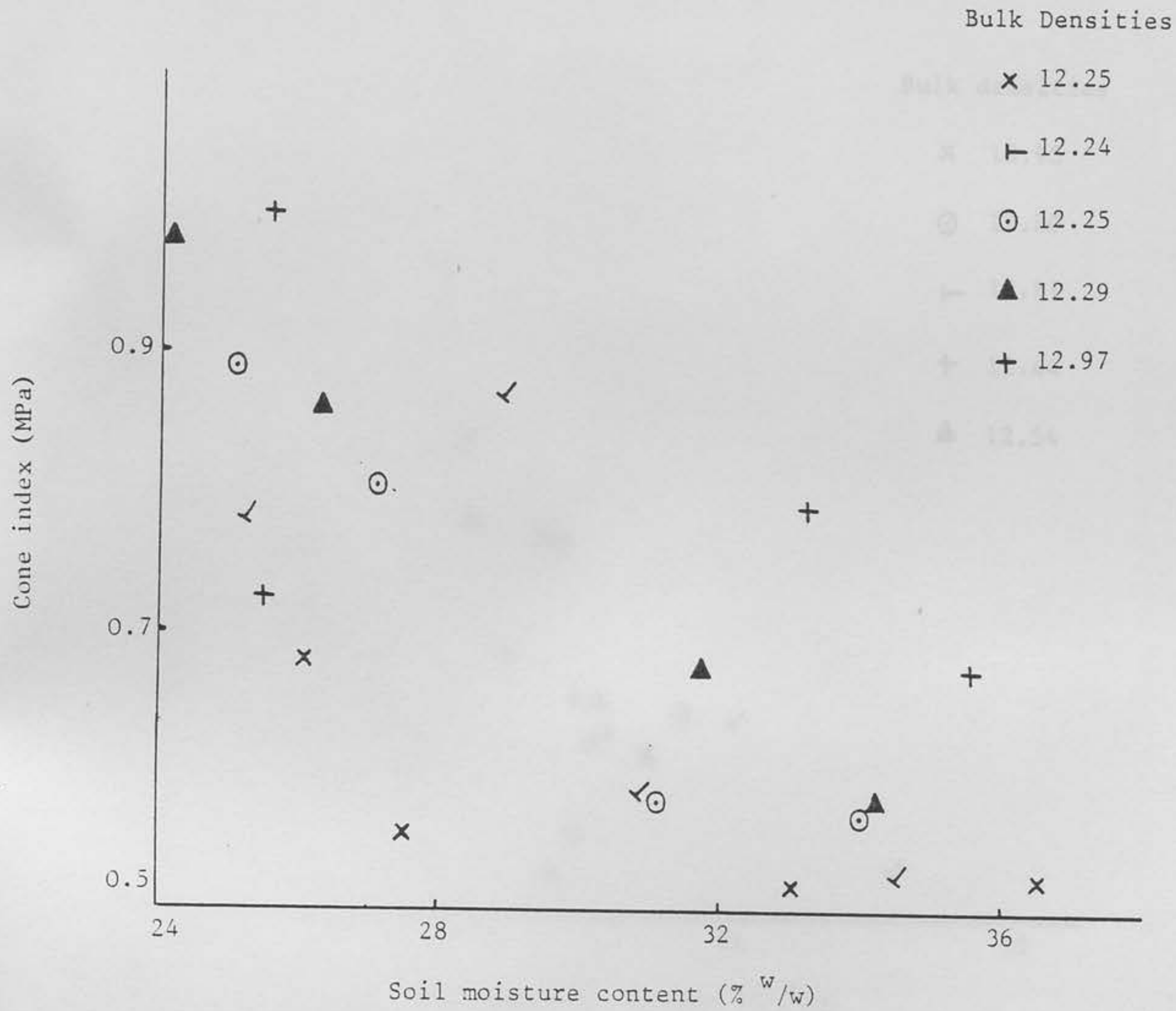

FIG. 5.8: Variation of cone index with varying soil moisture content at different bulk density for Darvel series at Plover Hall.

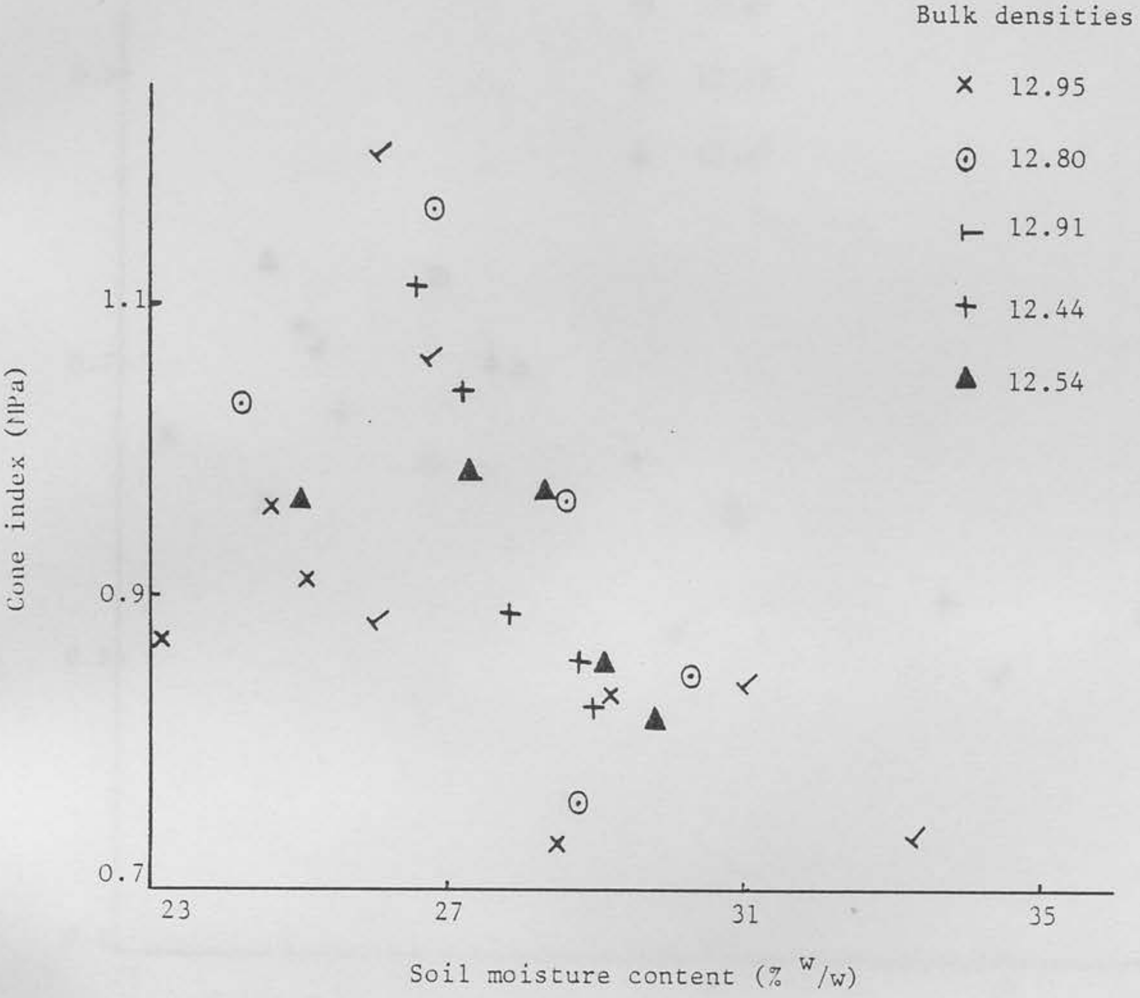

FIG. 5.9: Variation of cone index by varying soil moisture content at different bulk density levels for Macmerry soils at Longrig.

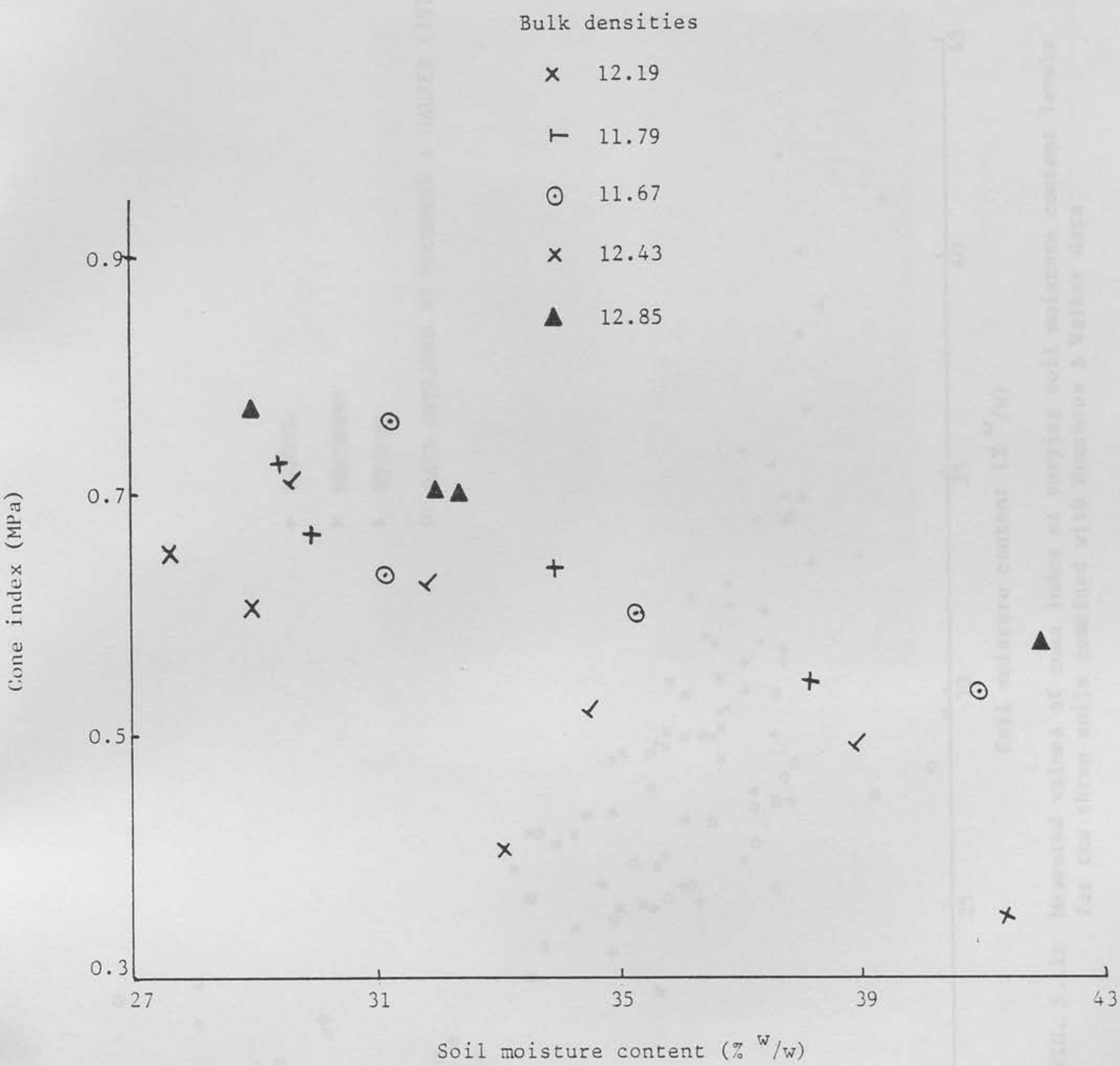

FIG 5.10: Variation of cone index with varying soil moisture content at different levels of soil bulk density for Winton soil at High Field.

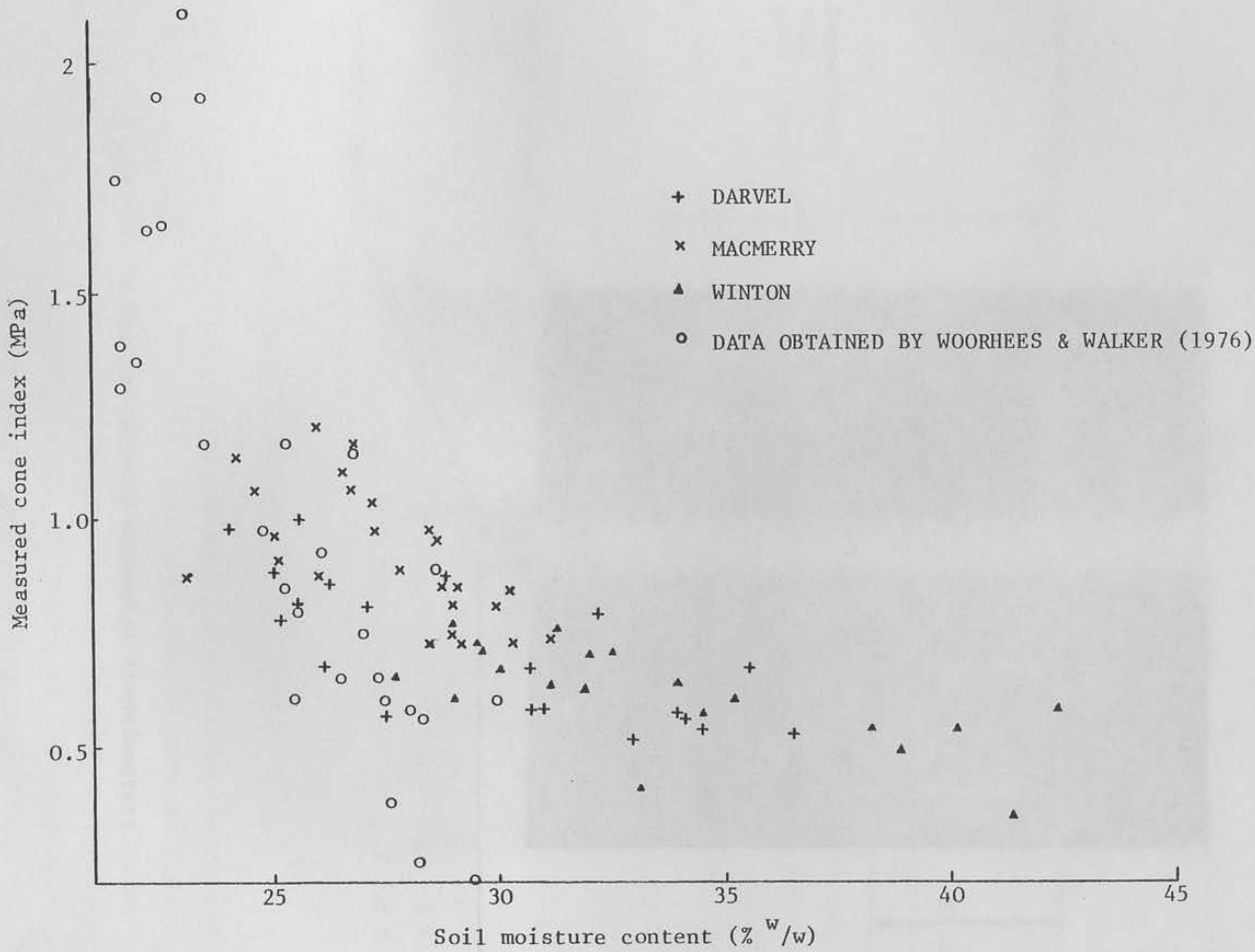

FIG. 5.11: Measured values of cone index at varying soil moisture content levels for the three soils combined with Woorhees & Walker data

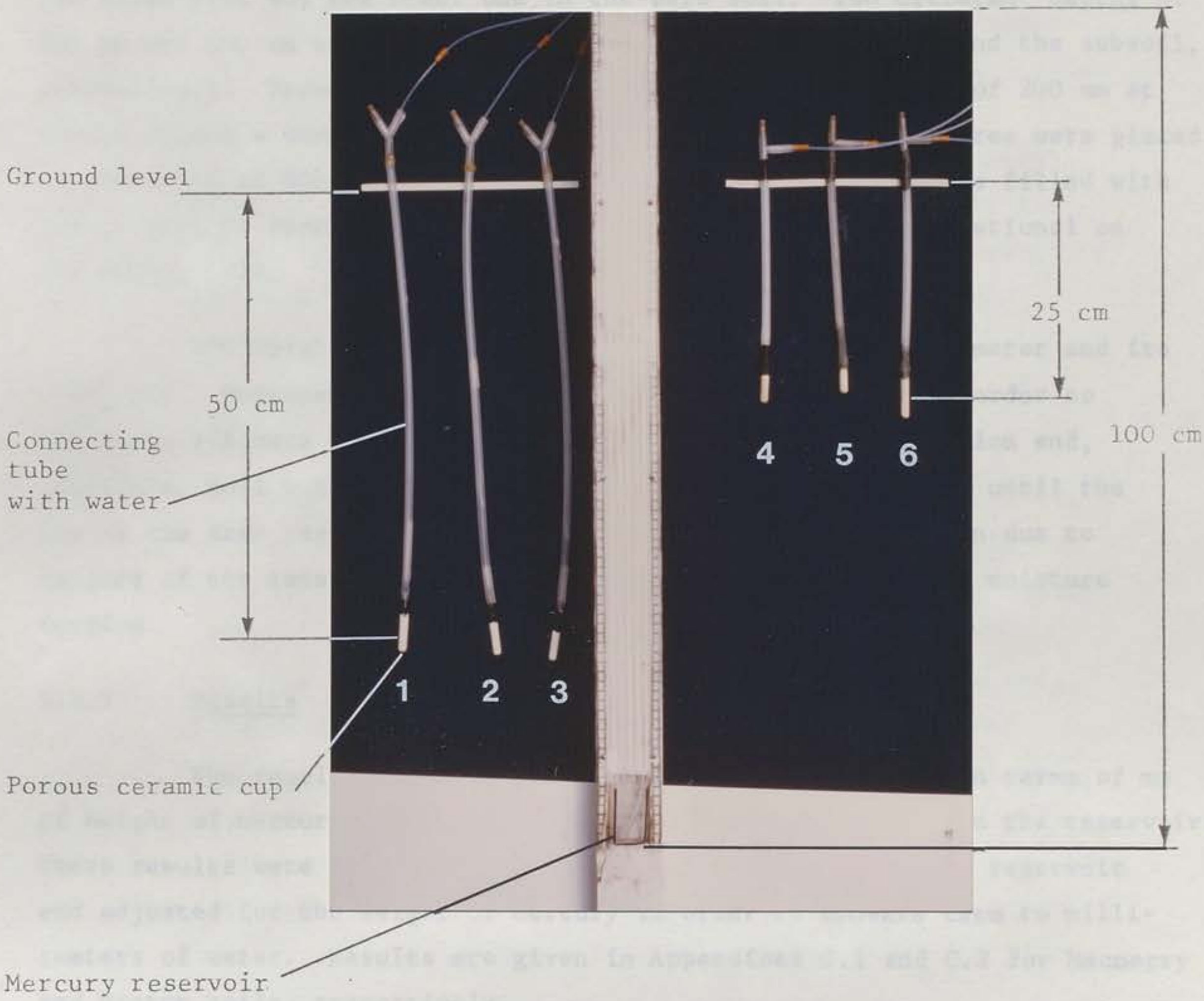

Plate 5.9: A Webster mercury manometer (tensiometer)

5.3.4 Procedure

Two of the four tensiometers were installed at each site, one in the grass plot and the other one in the bare soil. Two different depths of 200 mm and 400 mm were chosen to represent the plough layer and the subsoil, respectively. Three of the six cells were placed at a depth of 200 mm at random around a semi-circle of 1.5m diameter and the other three were placed at the depth of 400 mm in the same manner. The instrument was filled with water, left to reach to the equilibrium and became fully operational on 6th March, 1978.

The height of mercury was measured on both the manometer and its reservoir. Measurements were taken at 1-5 days intervals in order to obtain an adequate picture of fluctuations of soil water tension and, therefore, soil water content. These measurements were taken until the end of the same year with some breaks during the summer season due to failure of the tensiometers in the presence of excessive soil moisture tension.

5.3.5 Results

The results obtained from these tensiometers were in terms of mm of height of mercury column from the surface of the mercury in the reservoir. These results were corrected for the height of mercury at the reservoir and adjusted for the weight of mercury in order to convert them to milli-:meters of water. Results are given in Appendices C.1 and C.2 for Macmerry and Winton soils, respectively.

5.4 Measurement of Soil Moisture Characteristics

The objectives of this experiment are to obtain sufficient data to characterise the soils of the sites used for the soil moisture tension experiment and establish the soil moisture release curves in order to calculate the correlation coefficients between gravimetric soil moisture contents and soil moisture tensions and facilitate the conversion of tension data from previous experiment (5.3) to moisture content data.

5.4.1 Equipment

Cores and Sampling Equipment

Three sizes of cores were used namely: a) large cores which are cylinders of 76 mm outside diameter, 73 mm inside diameter and 50 mm depth made of stainless steel;
b) medium sized cores which are made of the same material and have 41mm outside diameter, 39 mm inside diameter and 20 mm depth; c) small cores which are used for sub-sampling are made of brass and have 28 mm and 25 mm outside and inside diameter respectively and 20 mm depth.

Tension Tables

Two perspex (polymethyl mathacrylate) tension tables were used. These tables were constructed according to specifications proposed by their original designer, Clement (1966). These tables are designed to facilitate the drainage of water to a known level of matric suction and are constructed from a perspex tray with dimensions of 15.8 mm, 305 mm, and 483 mm ($\frac{5}{8}$ x 12 x 19 in.) thickness, width and length, respectively, with 21 drainage channels. A filter paper membrane is used to equilibrate soil samples overnight up to 20 kPa of matric suction. These apparatus are protected from evaporation by means of aluminium lids which are not airtight.

Pressure Membrane

This apparatus which was originally designed by Richards (1941) to extract solutions from the soil under different matric suctions was altered at the U.S. Regional Salinity Laboratory to measure the amount of water drained from the soil at varying suctions (Richards, 1947). The apparatus consists of a chamber in which gas pressure can be increased above atmospheric pressure. The side of the chamber which supports the soil consists of a cellophane membrane supported on a brass screen and a brass plate in such a way that any watter passing through the membrane is conducted away at atmospheric pressure. A full description of the apparatus and its construction procedure is given by Richards (1947).

5.4.2 Sites, Soils and Procedure

The same sites and soils which were used in previous experiments were also used in this experiment.

Forty samples were taken with the large cores, ten from each depth of 250 mm and 500 mm for each of the two soils. The dolly which was placed over each core was pressed into the soil by means of the impact of a hammer and cores then were taken out, placed in polythene bags and sealed prior to transportation to the laboratory for the study. Each of these cores were then sub-divided in duplicate with the medium sized cores, one of which is weighed, dried and re-weighed to obtain the bulk density and the other placed on the tension table and saturated with water.

The soil moisture tension of the samples were stabilised first at 0.02, 0.05, 0.1 and 0.15 bar (2, 5, 10 and 15 kPa) and samples were weighed every time after a desired equilibrium was reached. Moisture content was calculated for these tension levels. In order to obtain higher tensions, each sample was sub-sampled in singles with small cores and was placed in the pressure membrane apparatus and was subjected to the gas pressures of 0.33, 1.00 and 3.00 bar (33,100 and 300 kPa), and weighed after reaching to the equilibrium.

5.4.3 Results

The soil moisture retained at a given tension was expressed in terms of grams of water in 100 grams of dry soil. The conventional unit of bar was used to express soil tensions. These results for two different soils at two different depths of 250 mm and 500 mm are given in Table 5.10. Variation of soil moisture content with changing tension are given in Figure 5.12. Soil water drained rapidly for values of low tension and more slowly for higher tensions. Curves in Figure 5.12 are very similar to the typical moisture release curves for these soils.

TABLE 5.10: Soil moisture characteristics data and bulk density of the two soils at two horizons measured at Langhill Farm.

Soil Type	HORIZON	SOIL MOISTURE TENSION, bar (kPa)							BULK DENSITY g/cm^3
		0.02 (2)	0.05 (5)	0.1 (10)	0.15 (15)	0.33 (33)	1 (100)	3 (300)	
		SOIL MOISTURE CONTENT, % $^w/_w$							
Macmerry	A	31.66	29.09	27.20	26.20	24.12	21.67	19.49	1.29
	B	15.67	12.09	11.15	10.53	8.79	7.08	5.72	1.54
Winton	A	30.08	27.36	25.99	25.12	23.32	21.15	19.20	1.27
	B	23.11	22.19	21.83	21.28	20.68	19.81	18.99	1.59

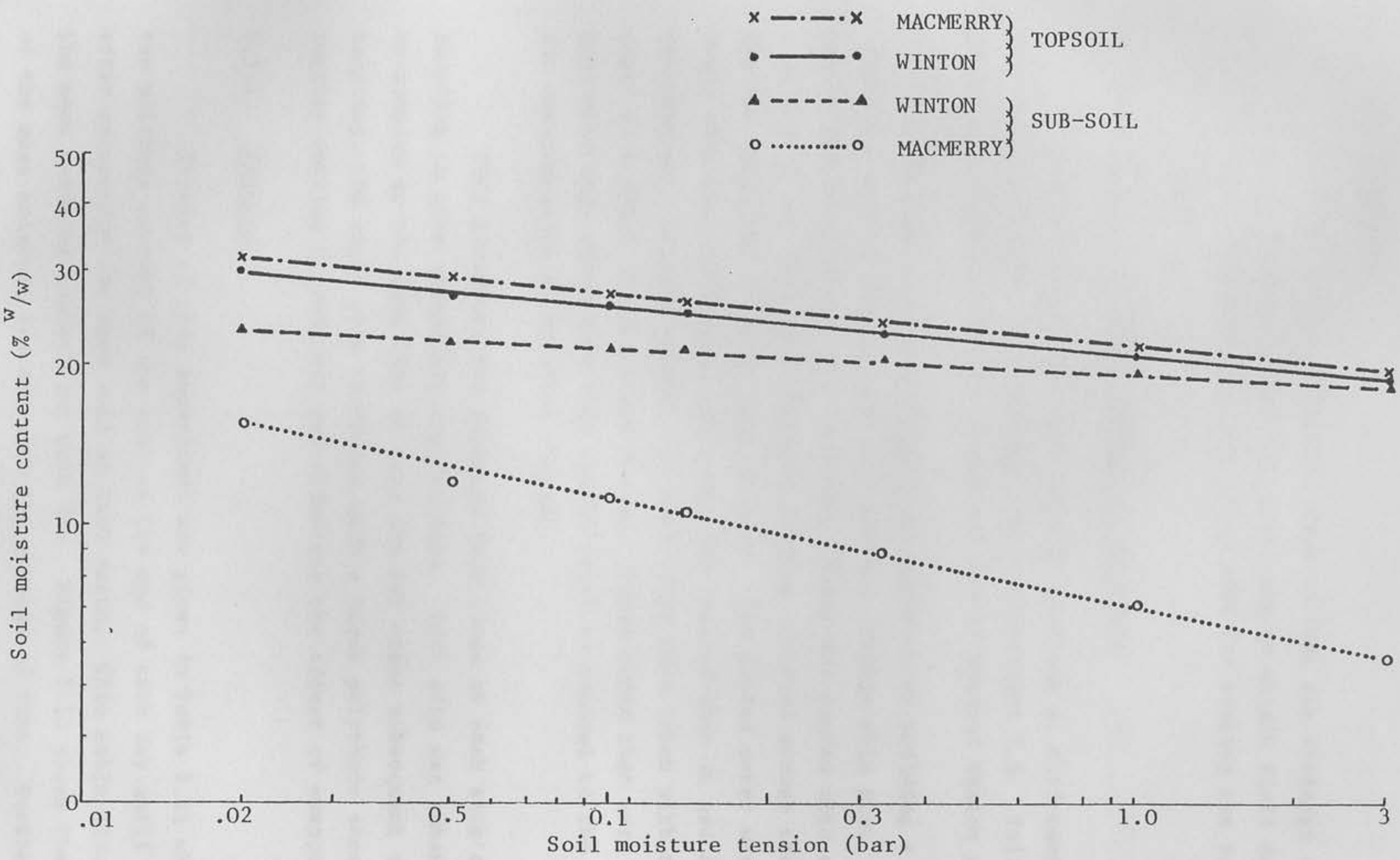

FIG. 5.12: Soil moisture content at different tensions for Macmerry and Winton soils at Langhill

5.5 Measurement of Soil Drainage

Objective

To obtain sufficient data to test the drainage component of soil moisture prediction model and to obtain field data on soil water properties of the sites used for testing the soil moisture model.

5.5.1 Equipment, Sites, Soils and Procedure

A screw auger was used for soil sampling at different depths of the sites at Langhill, Midlothian, as in experiment 5.3. Soils were moderately drained Macmerry series and poorly drained Winton series.

On each soil, a 4 m^2 plot was prepared by building a small retaining wall of 100 mm high with curves. Within this plot, the vegetation was killed by spraying with Paraquat. Water was poured into each plot over a period of two days until surface ponding occurred across the plots when further additions of water were stopped. The ponded water was allowed to drain from each plot until the point was reached when it had almost disappeared. At this moment, two soil cores were taken with the screw auger to a depth of 250 mm and 500 mm. These cores then were placed in polythene bags which were then sealed prior to removal to the laboratory for determination of moisture content.

This procedure was repeated four times at each site and for each sampling to give reasonable replications. Each site was subsequently re-sampled at the same time on each day for eight subsequent days. Between sampling, the sites were protected with a black polythene sheet to prevent further wetting by rainfall and eliminate the effect of evaporation.

5.5.2 Results

Results of this experiment are given in Table 5.11 which shows the moisture content of the soil at the end of each day until the 8th day after saturation for each soil at each depth. This table also contains the mean moisture content for each day. Figure 5.13 shows the variation of the mean moisture content with the passage of time. Further analysis of these results will be given in later stages of this work.

TABLE 5.11: Soil moisture content at the end of each day after saturation.

DAY NO	SAMPLE	SOIL MOISTURE CONTENT (grams of water/100 grams of dry soil)			
		MACMERRY SOIL		WINTON SOIL	
		TOP SOIL 0-250 mm	SUB SOIL 250-500 mm	TOP SOIL 0-250 mm	SUB SOIL 250-500 mm
1	1	50.20	35.96	49.19	20.12
1	2	41.74	24.64	35.27	23.00
1	3	57.72	30.71	45.50	19.15
1	4	47.49	31.49	41.34	21.58
	MEAN	49.28	30.70	45.34	20.96
2	1	35.27	23.07	50.31	24.06
2	2	39.51	22.32	38.88	24.30
2	3	40.54	23.15	37.97	25.03
2	4	39.32	20.59	33.90	15.24
	MEAN	38.66	22.28	40.09	22.15
3	1	37.27	29.95	44.45	24.26
3	2	40.40	26.94	41.24	23.38
3	3	44.45	27.83	38.84	23.60
3	4	35.95	30.37	42.39	25.00
	MEAN	39.52	28.77	40.82	24.06
4	1	38.02	26.98	41.84	21.95
4	2	37.93	28.70	39.47	20.88
4	3	38.45	27.30	37.50	23.83
4	4	37.36	29.87	32.84	24.53
	MEAN	37.94	28.21	39.60	22.52
5	1	39.66	23.53	41.19	23.15
5	2	32.36	23.11	39.71	24.84
5	3	39.42	19.51	37.36	21.80
5	4	38.40	25.07	35.86	23.93
	MEAN	37.46	22.80	37.64	23.20

TABLE 5.11 (Continued)

DAY NO	SAMPLE	SOIL MOISTURE CONTENT (grams of water/100 grams of dry soil)			
		MACMERRY SOIL		WINTON SOIL	
		TOP SOIL 0-250 mm	SUB SOIL 250-500 mm	TOP SOIL 0-250 mm	SUB SOIL 250-500 mm
6	1	36.51	27.04	36.46	22.20
6	2	36.28	26.99	36.04	27.85
6	3	32.03	25.68	37.59	23.26
6	4	34.92	27.03	36.85	23.02
	MEAN	34.93	26.68	36.73	24.04
7	1	31.85	27.27	32.73	18.60
7	2	34.18	25.52	33.43	25.00
7	3	31.37	25.82	33.36	19.44
7	4	34.77	24.75	35.34	22.72
	MEAN	33.04	25.84	33.71	21.44
8	1	31.89	29.63	35.13	21.37
8	2	34.12	27.08	36.43	23.22
8	3	34.31	26.89	32.08	25.32
8	4	33.92	25.96	36.62	23.18
	MEAN	33.56	26.11	35.05	23.27

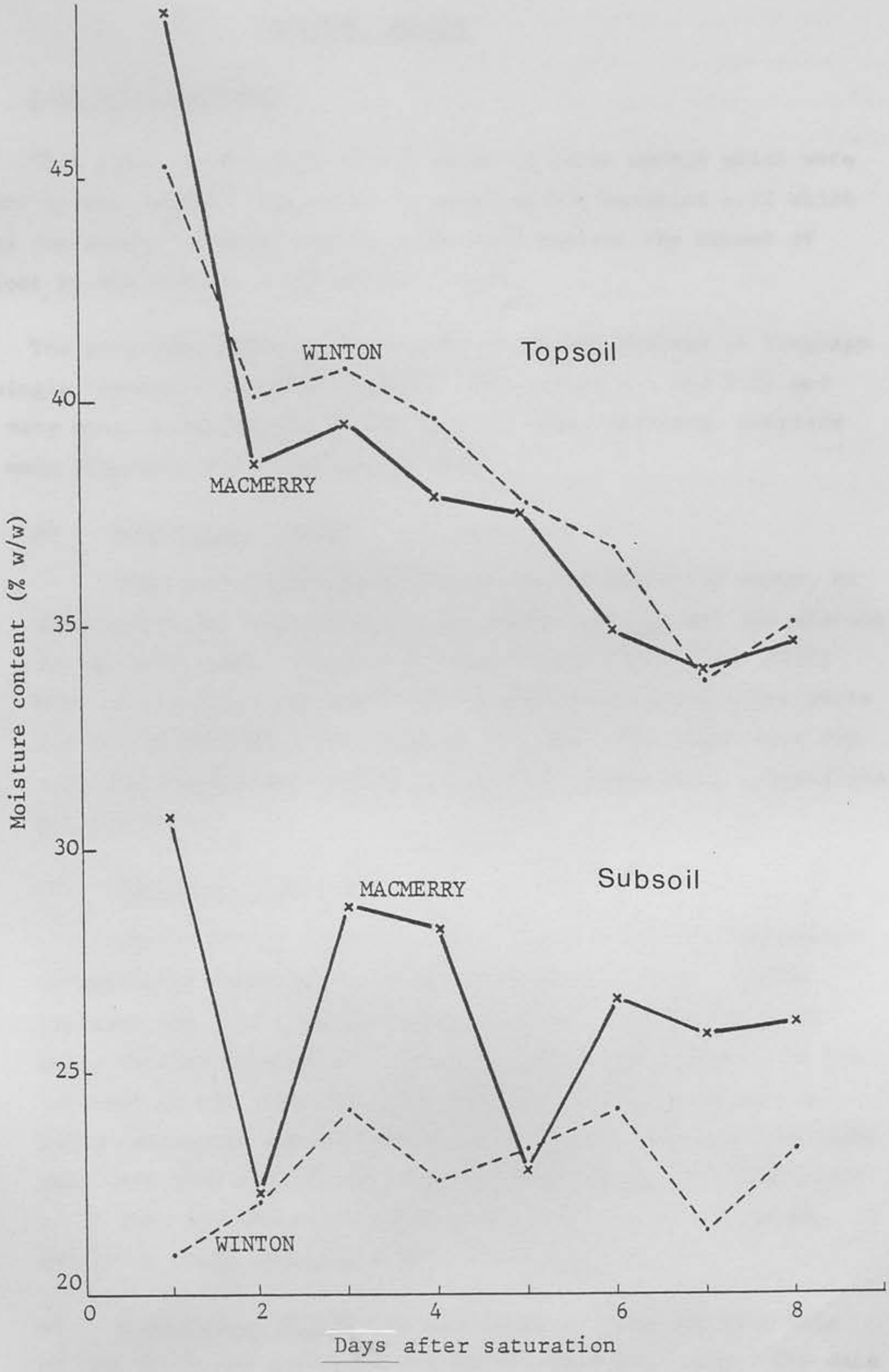

FIG. 5.13: Variation of soil moisture content with time after saturation.

6. COMPUTER MODELS

6.1 Soil Moisture Model

This model is the core of all other computer models which were developed in this study. The model is based on the equation 4.32 which balances the amount of water entering the soil against the amount of water lost by the soil in a 300 mm deep layer.

The programme which is written in Edinburgh FORTRAN 1V language for a single processor ICL 2980 computer (appendices D.1 and D.2) and with a very minor modification can be used on other machines, consists of one main programme and three subroutines:

a) Subroutine 'THORNS'

This subroutine was developed to calculate the amount of daily potential evaporation from monthly average air temperature for up to 21 years by means of equations 4.34 to 4.38. This part of the programme was made independent from the other parts and can be used as a programme on its own. The input data are only year number and monthly average air temperature (appendices D.3 and D.4).

b) Subroutine 'DAYLING'

The potential daylight hours required for the conversion of potential evaporation to actual evaporation for a given latitude are read from SMITHSONIAN tables (appendix D.6) by means of this subroutine. The only input data required is the latitude of the area for which the soil moisture content is being calculated and the SMITHSONIAN table. Potential daylight data were then transformed into an array of 24 x 36 dimensions to be used for the calculation of the day length correction factor by using equation 4.40.

c) Subroutine 'CLIMAT' is developed to scan the data file of the daily precipitation and actual sunshine hours. The data file is formed as a table with 25 x 12 x 31 dimensions in the order of year, month and day containing, date, sunshine hours and precipitation up to 25 years on a daily basis (appendix D.5). Conversion of the data from Imperial units to metric if necessary and transformation of the data into separate arrays for each year is also carried out in this subroutine.

d) The Main Programme operates as follows. First, the subroutines 'THORN', 'DAYLING' and 'CLIMAT' are called, daily potential evaporation for given number of years are calculated and the Smithsonian table, daily precipitation and actual hours of sunshine are read in. Then soil data such as soil moisture content and drainage at field capacity and saturation are also read in. The soil moisture content at the start of day 1 was assumed to be at field capacity and, therefore, the soil moisture deficit was zero. On this basis, different correction factors required in equation 4.33 were calculated and potential evaporation was adjusted by means of this equation. After calculation of drainage and run-off by means of equations 4.45 and 4.46 to 4.51, soil moisture content was calculated for the end of day 1 by using the equation 4.32. These following data and results were stored in a tabular form as the programme proceeded: daily precipitation, daily hours of sunshine, daily potential evaporation, correction factors, daily drainage, moisture deficit, moisture excess, moisture content and field capacity (appendix D.7, D.8). This process was repeated on a daily basis for the given number of years. A graph routine, 'GRAPH' (appendices D.9, D.10 and D.11) which contains two subroutines was also developed which facilitates the graphic presentation of the variation of soil moisture content with calendar date on a monthly basis. This routine later on was amalgamated into the main programme which directly produces the required graphs.

6.2 Workday Probability Prediction Model

This model which was developed for the prediction of soil workability with a known probability level is based on the soil moisture prediction model (appendices E.1 and E.2). This model was separated from the previous model to enable the independent use of the soil moisture model for other purposes such as prediction of irrigation requirement or soil moisture mappings.

The Work Day Probability Prediction Model (WDPPM) starts with prediction of soil moisture content as described in the previous section but, instead of producing the graphs and tables, moves to read the soil workability criteria. The maximum, minimum and incremental values of the workability criteria combined with the maximum, minimum and decremental values of the probability are read in (appendix E.3). The number of workability criteria and probability levels are then calculated by simply dividing the difference between the maximum and minimum values by decrement or increment. This figure can be up to 21 and 10 for the workability criteria and the probability, respectively. The soil moisture content is then tested against each of the workability criteria for every day and the day is assigned a work day (W) or non-work day (N) depending on its soil moisture level. This process is carried out on a daily basis for a given number of years.

The number of occasions being W or N were added up and divided by the total number of years in order to obtain the probability level. These figures also were tabulated for every workability criterion (appendix E.4). In order to obtain the total number of available days in a season, twelve periods of one month were chosen and the number of days with the same probability level in each month were added together and tabulated with the relevant workability criterion (appendix E.5).

Another shorter period of one week was also chosen, the same calculations carried out and weekly tables containing the number of available days in each week for every workability criterion and probability level was provided (appendix E.6). These tables were later on used in the machinery selection programme.

6.3 Machinery Selection Model

The programme was developed to select the optimum tractor power level required for tillage operations on a farm. The language used is

Edinburgh FORTRAN 1V and consists of the main programme and two sub-:routines (appendix H.1). Although this model is the continuation of two previous models, running costs are reduced by using a workday data file produced by WDPPM (appendix H.9).

The MAIN PROGRAMME which carries out all the readings of the data and calculations leading to the selection of feasible power levels from an engineering standpoint, starts with reading the costing data (appendix H.10) which are repair, resale and wear out groups; estimated machine life; inflation rate; interest on borrowed and initial capital and cost of unit fuel and labour, reading of the plough specifications and size boundaries, soil workability criterion and probability level boundaries and increments (appendix H.8).

The possible starting week, optimum finishing week and the maximum delay week numbers combined with coefficients of yield/time functions, commodity prices, area of the farm, soil specific weight and field capacity are also read at this stage.

The number of workday criteria and probability steps is calculated and the weekly workday table produced by WDPPM is read in. This leads to the calculation of the number of increments or decrements required for plough dimensions and travel speeds. Five levels of tyre/weight/deflection data are stored in the form of block data which could be used as required.

The following initial conditions were set:

- maximum speed;
- maximum number of plough bodies;
- maximum depth of cut;
- minimum workability criterion;
- maximum design probability;
- minimum tractor weight;
- minimum tyre size;
- optimum slip.

Cone index is calculated by means of equation 4.9 and wheel mobility number was obtained from this value of cone index using equation 4.8

from which tractive efficiency, actual pull, theoretical pull, rolling resistance, slip and tractor power are calculated using equations 4.1 to 4.7. Plough draught is calculated using equation 4.18 and then tested according to the conditions, a to e in section 4.3. If these conditions were satisfied, work rate of the plough, number of hours required and number of days required to complete the task are calculated by means of equations 4.28 to 4.30, but, if they were not satisfied a decrement is deducted from the maximum speed and all calculations and tests are repeated keeping the rest of the variables unchanged. This is repeated until all the conditions are met. If, during this process, the speed level is reduced below the minimum allowable speed (defined in the input data) without the conditions being met, a decrement is deducted from the number of plough bodies while the speed is re-set to the maximum and the whole procedure is repeated. In this way all combinations of the variables are examined and if any of the results meet the conditions they are retained for further analysis, otherwise a prompt message of 'OPERATION IMPOSSIBLE' is printed and the programme is terminated.

Tyre size and tractor weight also is varied in the same manner. Satisfactory results then are transferred to subroutine 'MAC' in order to test against available time.

a) <u>Subroutine 'MAC'</u>

The following terms and assumptions have been used in this subroutine. WK1, the possible starting week, is the week number of the year at which the start of plough operation becomes possible; WK2, desirable finishing week, is the week number of the year by which if the ploughing is completed no timeliness penalties will incur; WKM, week maximum, is the number of the week after which the delay on operation becomes unacceptable (due to excessive timeliness penalties).

This subroutine is designed to test the amount of days required against the amount of workdays available calculated from the WDPPM (appendix H.3 and H.4). For the lowest (driest) workability criterion and the highest probability level, the number of days available in the first week is compared with the days required. If the number of available days exceeded the number of required days, the costing routine is called, otherwise, the days available in the second week are added and the comparison is repeated until either the condition is met or the week number exceeds the maximum, WKM. In the former case, another test is carried out to find out whether the week number exceeds the WK2 thereby incurring a timeliness penalty. In this case, the timeliness penalty is calculated using equation 4.64. In the latter case, the combination is rejected and the second lowest workability criterion is chosen while the process beginning with the calculation of cone index is repeated for the new moisture level. This is done for all of the workability criteria and satisfactory tractor/plough combinations are transferred for cost calculation.

b) <u>Subroutine 'COST'</u>

The subrountine is a new version of a costing programme developed at the N.I.A.E. by Audsley and Wheeler (1978) which calculates the present annual cost of owning farm machinery (appendix H.5 and H.6). The hours required to complete the task, tractor power level, number of plough bodies and other necessary input data are transferred from the previous subroutine and the main programme. The list prices of tractors and ploughs are calculated from their sizes by means of equations 4.69 and 4.70, respectively. Typical wear out life data are stored in the form of block data and used to calculate the machine salvage value by means of equation 4.67 and Table 4.3. Repair costs are also calculated and adjusted for inflation rate and interest rates inserted in equation 4.68 and Table 4.4. These values then are used to solve the equation 4.65 and calculate the present annual costs of the machine.

The fuel cost and labour cost for ploughing operations only and for the whole tractor usage is calculated by means of equations 4.72 and 4.71, respectively. These results are stored and then the whole process except fuel and labour cost calculation is repeated for the plough. These costs are presented in a tabular form combined with timeliness penalty costs and total system costs for all the feasible systems(Appendix H.11). A more detailed table of information containing engineering, pedological, agronomic, operational and economic information for each system is also presented for further consultation (Appendix H.12).

6.4 Soil Moisture Tension Models

6.4.1 Tension 1

The model is developed to handle large amounts of data obtained from the tensiometers and to carry out the necessary calculations in order to convert them to bar or kpa (appendix F.1).

The data are read-in from tables similar to appendices C.1, C.2 and F.2 for each soil type for up to ten years. Data for each depth are then averaged and adjusted for the height of mercury reservoir and for the bulk density of mercury (appendix F.3 and F.4). The results are converted to mm of water or bars and stored in separate files.

6.4.2 Tension 2

This model which is written to convert the tension data obtained from the previous programme into mm of water in a given depth of soil or percentages of water on a dry basis consists of the main programme and a subroutine (appendix G.1).

Subroutine 'TENAT' reads the data produced from the previous programme (TENSION 1) for one soil, one depth and up to ten years at a time.

The main programme reads the soil bulk density, depth and the coefficients of the soil moisture characteristic curves and converts the data read by 'TENAT' into grams of water in 100 grams of soil or mm of water in a given depth of soil. The outputs are presented in two separate tables, one for consultation which contains date, soil tension and soil moisture content (appendices G.2 to G.9) and the other one for the use by the graph programme which only contains soil moisture data for every day of the year.

6.5 Other Minor Programmes

These programmes which were designed to carry out lengthy calculations such as calculation of soil bulk density, soil moisture content and some other calculations can be used independently for other purposes.

A multiple regression package available on the Edinburgh Multiple Access System (EMAS) is used for statistical analysis of results and fitting curves, when necessary.

7. ANALYSIS OF RESULTS AND DISCUSSION

7.1 Soil Moisture Content

To test the soil moisture content prediction model two sets of results were used as follows:

- results from the Soil Survey of Scotland;
- results from the tension experiment.

7.1.1 Preliminary Test of the Model

No published data is available for the daily fluctuation in moisture content in Scottish soils but the Soil Survey of Scotland was able to provide figures for the weekly values of soil moisture tension in three soil series namely: Darvel, Macmerry and Winton in Central Scotland for 1972, 1974 and 1976 (Duncan, 1979). The data for the intervening years were insufficiently complete. The specifications and drainage characteristics of these soils have been given in Chapter 5.

A preliminary test of the soil moisture prediction model was carried out using these data.

Using the tension program, TENSION 2, the soil moisture tension was converted into millimeters of water moisture in the top 300 mm of the soil profile using soil moisture characteristics and bulk densities supplied by the Soil Survey of Scotland (Duncan, 1979). These data for horizons, A and B for the three soils combined with their soil bulk densities are given in Table 7.1. Figure 7.1 shows the variation of soil moisture content at various soil moisture tensions. A logarithmic equation in the following form was fitted to all the data and a very high degree of explanation was obtained for each soil type and horizon:

$$M = \mathrm{Exp}\ (C_1 + C_2\ \ln TN) \qquad 7.1$$

where: M is soil moisture content (% w/w)
C_1 and C_2 are constants
TN is soil moisture tension (bar)

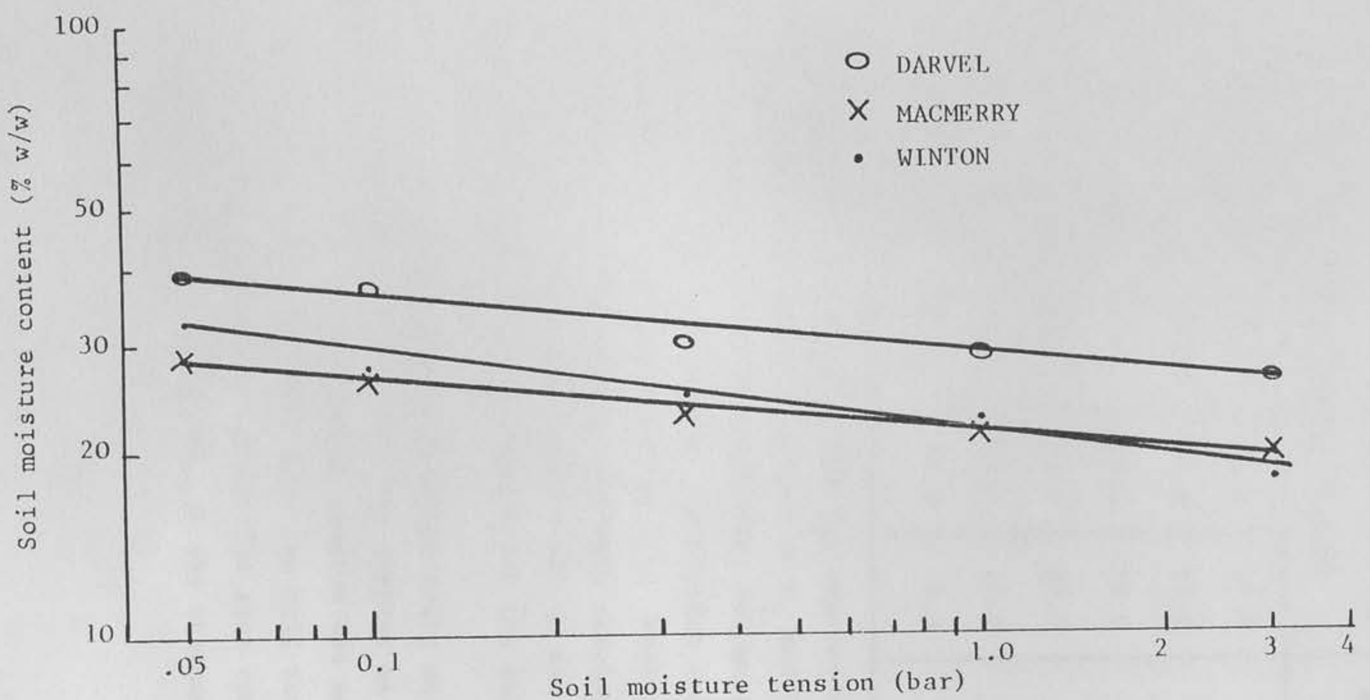

FIG. 7.1: Soil moisture content at different tensions for Darvel, Macmerry and Winton soil series at plough layer.

(Ragg 1976)

TABLE 7.1: Soil moisture characteristics data combined with bulk and particle densities for the three soils at two horizons for preliminary test.

SOIL TYPE	HORIZON	SOIL MOISTURE TENSION (bar) 0.05	0.1	0.33	1	3	BULK DENSITY g/cm^3	PARTICLE DENSITY g/cm^3
		SOIL MOISTURE CONTENT (% w/w)						
MACMERRY	A	28.5	26.7	23.4	22.1	19.8	1.1	2.56
	B	27.0	24.3	17.9	15.8	13.3	1.5	2.66
WINTON	A	38.7	37.2	30.2	29.2	26.6	1.1	2.58
	B	32.1	30.3	24.4	21.5	20.8	1.6	2.65
DARVEL	A	32.5	27.7	24.8	21.9	17.8	1.2	2.54
	B	22.6	18.0	13.5	10.7	8.3	1.4	2.69

Table 7.2 summarises the values of C_1 and C_2, degrees of explanation, coefficients of correlation, and standard errors on C_1 and C_2 for the three soils. Other types of equations such as parabolic, hemographic and linear were also tried but the best fit and highest correlation coefficient was obtained with the equation of the form equation 7.1. Weekly values of soil moisture content obtained from the tension data were tabulated for each soil type at two different depths, the plough layer 0-300 mm and the sub-soil 300-500 mm but only the former will be discussed for the purpose of this study.

Daily figures of rainfall and actual sunshine hours and mean monthly values of air temperature were obtained from the nearest meteorological stations to the sites where the soil moisture tension was measured. Although those stations varied from 3-5 km distance from the soil tension measurement sites it was considered that they would reflect the site conditions sufficiently accurately to justify their use, in the absence of better data.

TABLE 7.2: Values of C_1 and C_2, standard errors on C_1 and C_2, correlation coefficients and degrees of explanation of the data within 95% confidence limit for the three soils used in preliminary test (equation 7.1).

SOIL TYPE	HORIZON	C_1	C_2	STANDARD ERROR C_1	STANDARD ERROR C_2	CORRELATION COEFFICIENT	% EXPL
MACMERRY	A	2.9737	- 0.1523	0.063	0.031	0.9236	85.31
	B	2.78760	- 0.1573	0.024	0.012	0.9884	97.69
WINTON	A	3.23258	- 0.17586	0.080	0.040	0.9101	82.83
	B	3.07650	- 0.1375	0.028	0.014	0.9797	95.97
DARVEL	A	2.9443	- 0.2004	0.061	0.030	0.9557	91.35
	B	2.4003	- 0.2181	0.023	0.011	0.9943	98.86

To test the soil moisture prediction model, the programme was run for each soil series using the above-mentioned figures and soil data (Table 7.3). For the Winton and Macmerry soils it was assumed that the field capacity was equivalent to 0.05 bar tension and the appropriate moisture content taken from the soil moisture characteristics were 110 and 92 mm/300 mm of soil profile.

TABLE 7.3: Soil moisture tension, soil moisture content and drainage at saturation and field capacity for soils used for preliminary test.

SOIL TYPE	SOIL MOISTURE TENSION (bar)		SOIL MOISTURE CONTENT (mm/300 mm soil)		DRAINAGE (mm/day)	
	SATURATION	FIELD CAPACITY	SATURATION	FIELD CAPACITY	FIELD CAPACITY	SATURATION
DARVEL	0.0001	0.1	184	90	0.1	1000
MACMERRY	0.0001	0.05	126	92	0.18	180
WINTON	0.0001	0.05	170	110	0.05	5

For the Darvel series a tension of 0.1 bar was considered more appropriate and the corresponding moisture content was 90 mm/300 mm soil profile. A tension of 0.001 was assumed to be near enough to zero tension and all the three soils were assumed to be at saturation at this tension. The corresponding soil moisture contents, drainage at this tension and drainage at the field capacity combined with soil moisture tensions and contents at field capacity are given in Table 7.3.

The results for predicted daily average soil moisture content in the top 300 mm of each profile combined with the daily values of rainfall and weekly measured soil moisture content converted from the soil moisture tension data, for each soil series, for each year are given in Figures 7.2-7.4.

Macmerry Series

Throughout January and February 1972 (Figure 7.2) the actual moisture content fluctuated between the equivalent of 98 and 105 mm of moisture in the upper 300 mm of the profile. A steady decline in moisture content to a low value of 88 mm occurred between early March and mid-April when following heavy rain, the soil moisture content rose to 105 mm of water. Thereafter, the moisture content declined rapidly and fluctuated only slightly around a value of 78 mm until the end of October when it rose rapidly to 110 mm before settling down to values between 92 and 101 mm for the remainder of the year. The pattern of variation in moisture was similar in 1974 and 1976 (Figures 7.3 and 7.4).

The predicted soil moisture contents followed the same pattern as those measured but the amplitudes of the short term fluctuations were slightly greater. For example, in the period January to March 1972, the predicted moisture content ranged from 96 to 109 mm. The period of drying out in the summer was accurately predicted by the model but the actual extent of drying out was over-estimated by approximately 15 mm (Figure 7.2).

In 1976, the same general trend occurred but in this year, the predicted soil moisture content was consistently greater than that measured except in the very dry mid-summer period, when the model again over-estimated the amount of drying by around 15 mm. The date of rapid drying out of the soil in early summer was one week later than that predicted (Figure 7.4).

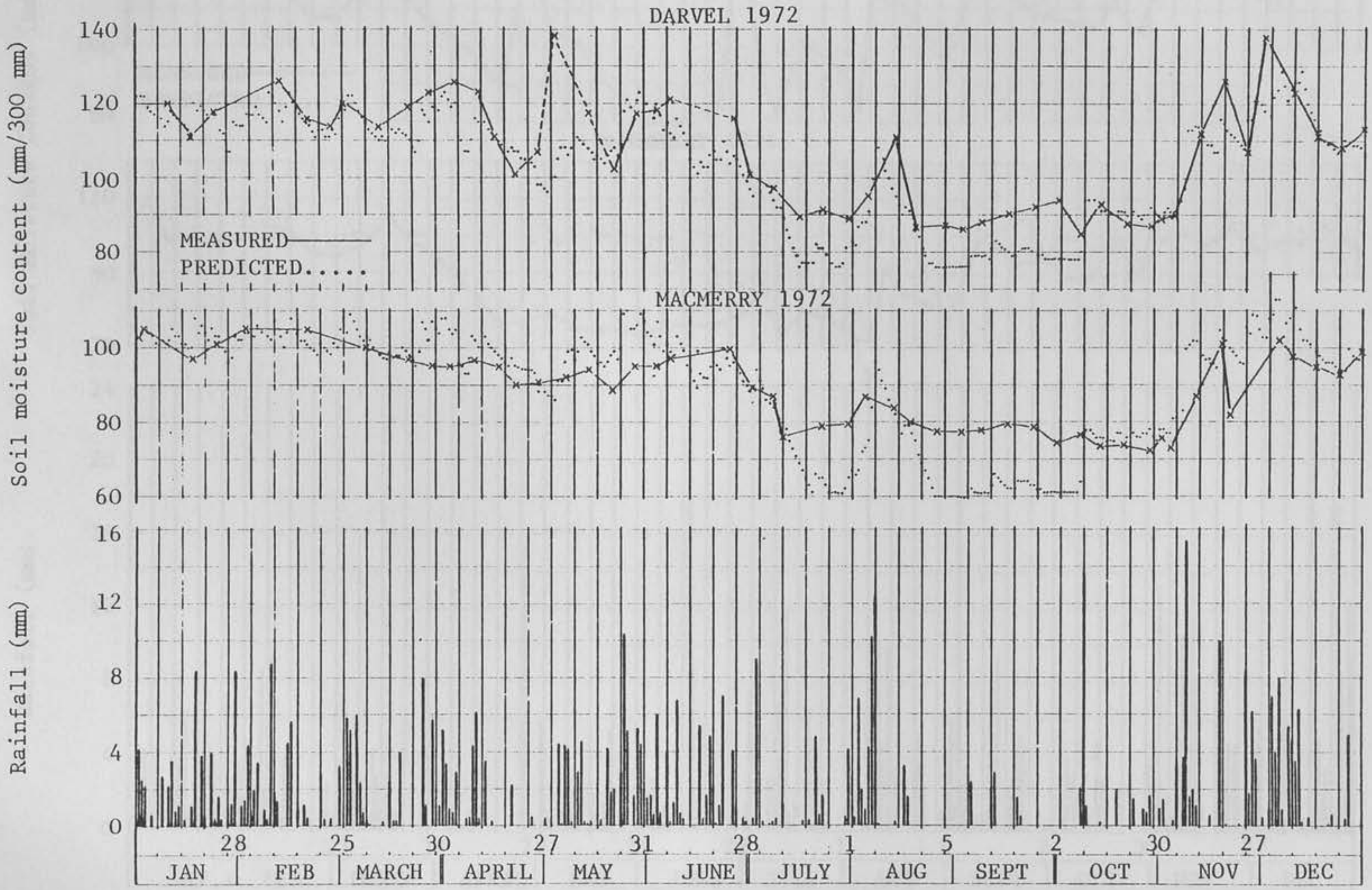

FIG. 7.2: Comparison of measured and predicted soil moisture content in the plough layer (300 mm) with grass cover for Darvel and Macmerry soil series in relation to precipitation during 1972.

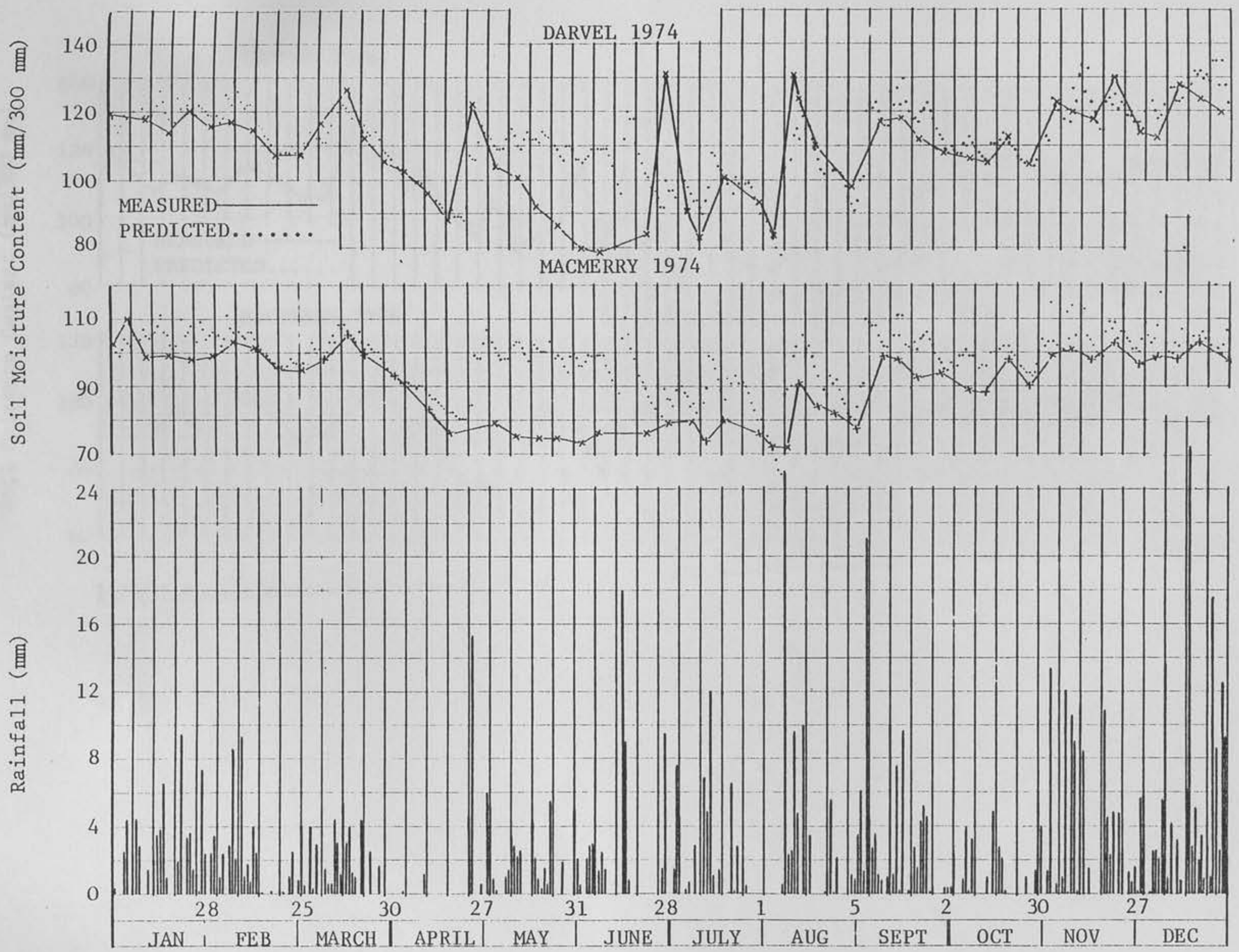

FIG. 7.3: Comparison of measured and predicted soil moisture content in the plough layer (300 mm) with grass cover for Darvel and Macmerry soil series in relation to precipitation during 1974.

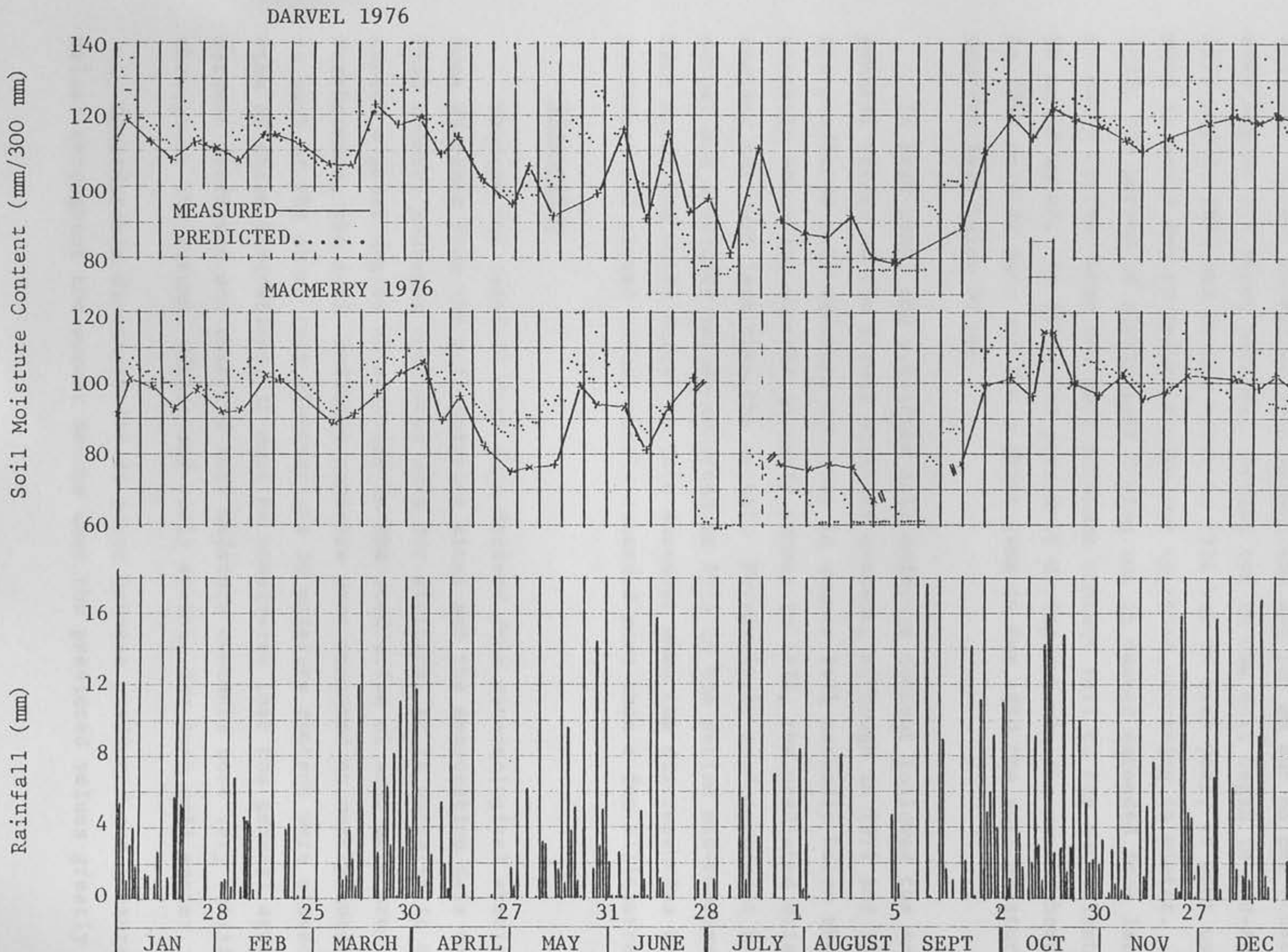

FIG. 7.4: Comparison of measured and predicted soil moisture content on the plough layer (300 mm) with grass cover for Darvel and Macmerry soil series in relation to precipitation during 1976.

Darvel Series

The variation in the actual moisture content in the Darvel series was generally much greater than that occurring in the Macmerry series, both on a weekly and a long term basis. In the winter months, the actual soil moisture content generally fell betwen 115 and 130 mm but on one occasion went even higher for short periods. Drying out in the soil began in mid-April in 1972 and in 1976 and in mid-March in 1974 but in each year, it went up once more in early May to values equivalent to those occurring in winter. In 1972, the period of significant drying out in summer extended from late June to early October when the soil moisture content fell to the equivalent of 90 mm of water. In 1976, the period of drying out was one month shorter. In 1974 only in July and for a short time in May, did the soil moisture content fall below 90 mm.

In each year, the predicted soil moisture content followed the same general trends as the actual moisture content, although in 1972 and 1976, the predicted soil moisture contents in summer fell markedly below those actually occurring whereas in early summer in 1974, the predicted moisture content was much less than the actual. Particularly good agreement between actual and predicted values occurred in 1974 in the period mid-February to late April and early August to late November when the discrepancies between predicted and actual values rarely exceeded more than a few millimetres.

Discussion

Because the rainfall data were derived from meteorological stations some distance from the soil moisture sites and the evaporation data were from country averages corrected only for altitude, it is unrealistic to expect a great degree of accuracy in the prediction of soil moisture content. Furthermore, the soil moisture contents were measured at weekly intervals so much of the short term fluctuations in moisture content were missed. In view of these limitations, it must be considered that the general agreement between predicted and observed soil moisture contents were very satisfactory throughout the autumn, winter and early spring, for both soil series.

Considerable discrepancies do occur between predicted and measured values throughout the summer months when the predicted values greatly exceed those measured. This may be an artefact. In July of each year, the soil moisture tensions increased to values in excess of 300 millibars and reached values in excess of 800 millibars. It is generally accepted that in soils drier than 300 millibars, porous cup tensiometers are unreliable and at values in excess of 600 millibars, they can considerably underestimate the moisture content. As the soil shrinks on drying, contact between the cup and the soil becomes less than satisfactory at higher tensions. Alternatively the cup may be pulled away from the tensiometer tube. It is highly probable, therefore, that the true soil moisture content does exceed significantly that measured and that the model still gives a reasonable prediction.

This does not explain those occasions in spring when the measured soil moisture content was less than that predicted. One possible source of discrepancy is that the model predicts the moisture content in the upper 300 mm of the Profile. The tensiometers measure only the moisture content at one point in the profile and in the procedure used here, this moisture content is assumed to represent that throughout the profile. In periods with high evaporation from the soil and frequent low volume rainfall events, it is possible that the upper few centimeters of the soil are in fact wetter than the soil at tensiometer depth. In other words, the tensiometers underestimate the total water content in the profile.

The problems of unequal moisture content within the profile are illustrated by the measured soil moisture contents in the Darvel series in later June 1974. The soil measurements indicate that the soil moisture content increased by 46 mm but in that month the rainfall was only 26 mm.

7.1.2 Second Test of the Model

Another test of the soil moisture prediction model was made using the data obtained from the results of the experiment 5.3 (Appendices C.1 and C.2).

Using the program, TENSION 1, these figures were averaged for each depth, soil, surface cover and day of measurement, corrected for the height and bulk density of the mercury in the reservoir and converted into bars of pressure.

The following equation suggested by Webster (1865) was used:

$$TN = 12.6\ MAN - 13.6\ RES - H \quad 7.2$$

where: TN is the soil moisture tension (cm of water); MAN is the level of mercury in the manometer; RES is the level of mercury in the reservoir; H is the depth below the zero of the scale of the highest part of the porous pot exposed to the soil.

Resultant data from this programme then were converted into mm of water in top 300 mm of soil profile by means of the programme, TENSION 2 using soil moisture characteristics and other soil data (Table 5.10). The equation 7.1 was fitted to the soil moisture characteristics data obtained for two soil types of Macmerry and Winton from the experiment (5.4). The following values for C_1 and C_2, standard error on C_1 and C_2, correlation coefficient and the degree of explanation of the data within 95% confidence limit were obtained (Table 7.4).

TABLE 7.4: Values of C_1 and C_2, standard errors on C_1 and C_2, correlation coefficients and degrees of explanations of the data within 95% confidence limit for the two soils used in secondary test.

SOIL TYPE	DEPTH (mm)	C_1	C_2	STANDARD ERROR C_1	STANDARD ERROR C_2	CORRELATION COEFFICIENT	% EXPL
MACMERRY	300	3.0762	- 0.0965	0.0050	0.0017	0.9997	99.93
	600	1.9584	- 0.1945	0.0296	0.0296	0.9775	95.56
WINTON	300	3.05208	- 0.08803	0.01339	0.0046	0.9973	99.45
	600	2.9866	- 0.0388	0.01125	0.00388	0.9902	98.04

Soil moisture content values obtained from this programme were tabulated for each soil, depth, surface cover and the day of measurement.

Daily figures of rainfall and actual sunshine hours and mean monthly air temperature for the sites were obtained from the meteorological station at Bush Estate, Midlothian, which is about 2 km away from the Langhill farm where the soil moisture tension was measured. Other soil data required, soil moisture content and hydraulic conductivity at saturation and field capacity was measured on site (experiment 5.5) and are given in Table 7.5.

TABLE 7.5: Soil moisture tension, soil moisture content and drainage at saturation and field capacity for the soils used the second test.

SOIL TYPE	SOIL MOISTURE TENSION (bar)		SOIL MOISTURE CONTENT (mm/300 mm soil)		DRAINAGE (mm/day)	
	SATURATION	FIELD CAPACITY	SATURATION	FIELD CAPACITY	SATURATION	FIELD CAPACITY
MACMERRY	0.001	0.01	190	133	32.3	0.90
WINTON	0.0001	0.05	175	138	21.3	0.57

The soil moisture predictions model was run for two soils with two surface covers for the year 1978 using these data. A crop stage correction factor was obtained from the Figure 3.12 and included in the calculation when soil moisture content was being predicted under grass cover. These values of soil moisture content for each day were tabulated and then plotted with corresponding soil moisture content values obtained from the tension data combined with the corresponding rainfall for that day. Figures 7.5 and 7.6 shows these results for the Macmerry and Winton soils for the depth of 300 m respectively.

For Macmerry series on the grass plot when the measurements started in March, the soil moisture content was approximately 112 mm. On the grass plot, it remained at this level with only very minor fluctuations until the last week in May when it declined steadily to 95 mm. It remained at a low level throughout the summer with minor peaks on 28th June and 11th July, until early September when it began to rise, slowly at first, then more rapidly to reach a peak of 118 mm in October. Following a dry month it

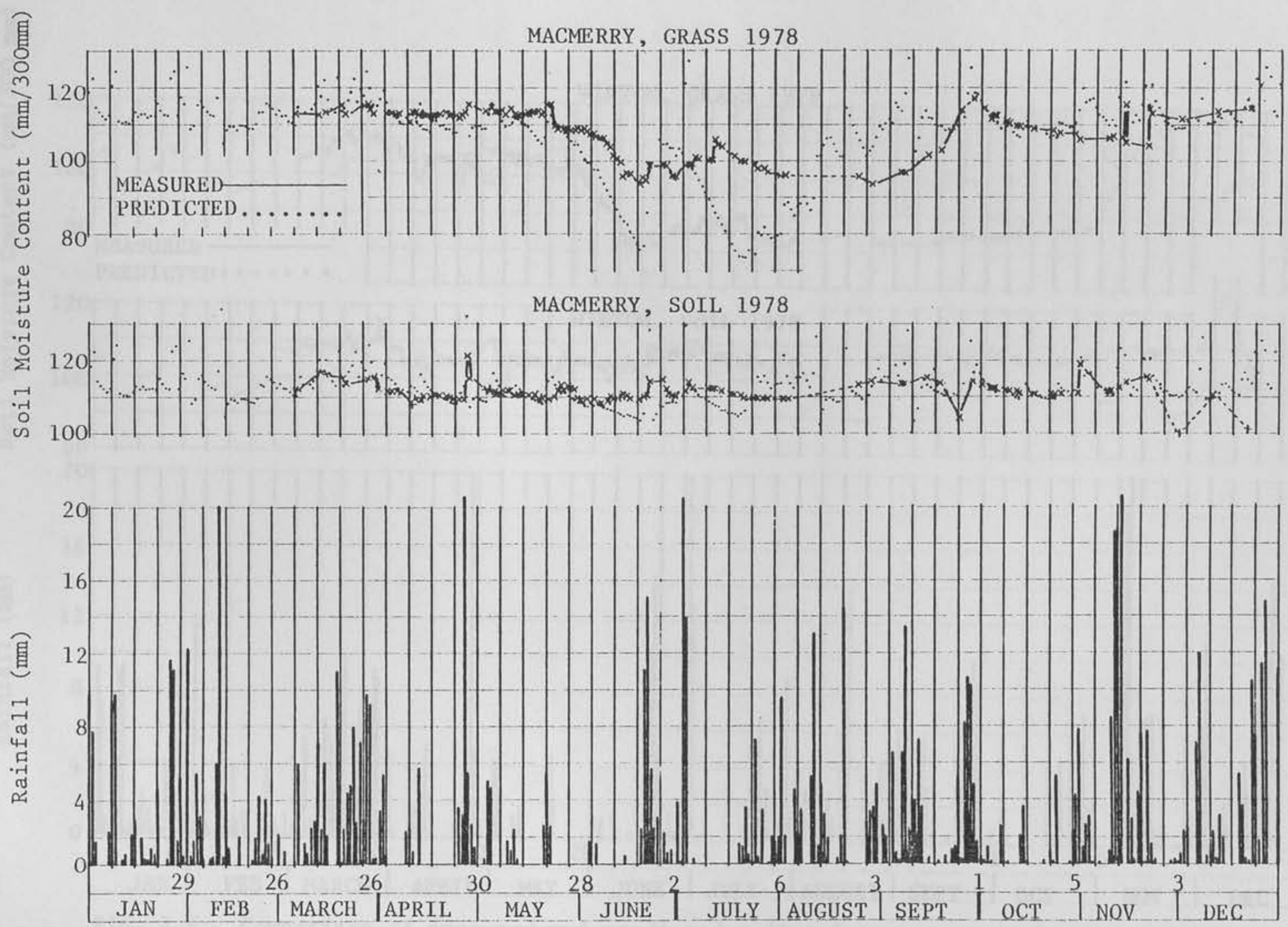

FIG. 7.5: Comparison of measured and predicted soil moisture content in the plough layer (300 mm) with grass cover and bare soil for MacMerry soils in relation to precipitation during 1978

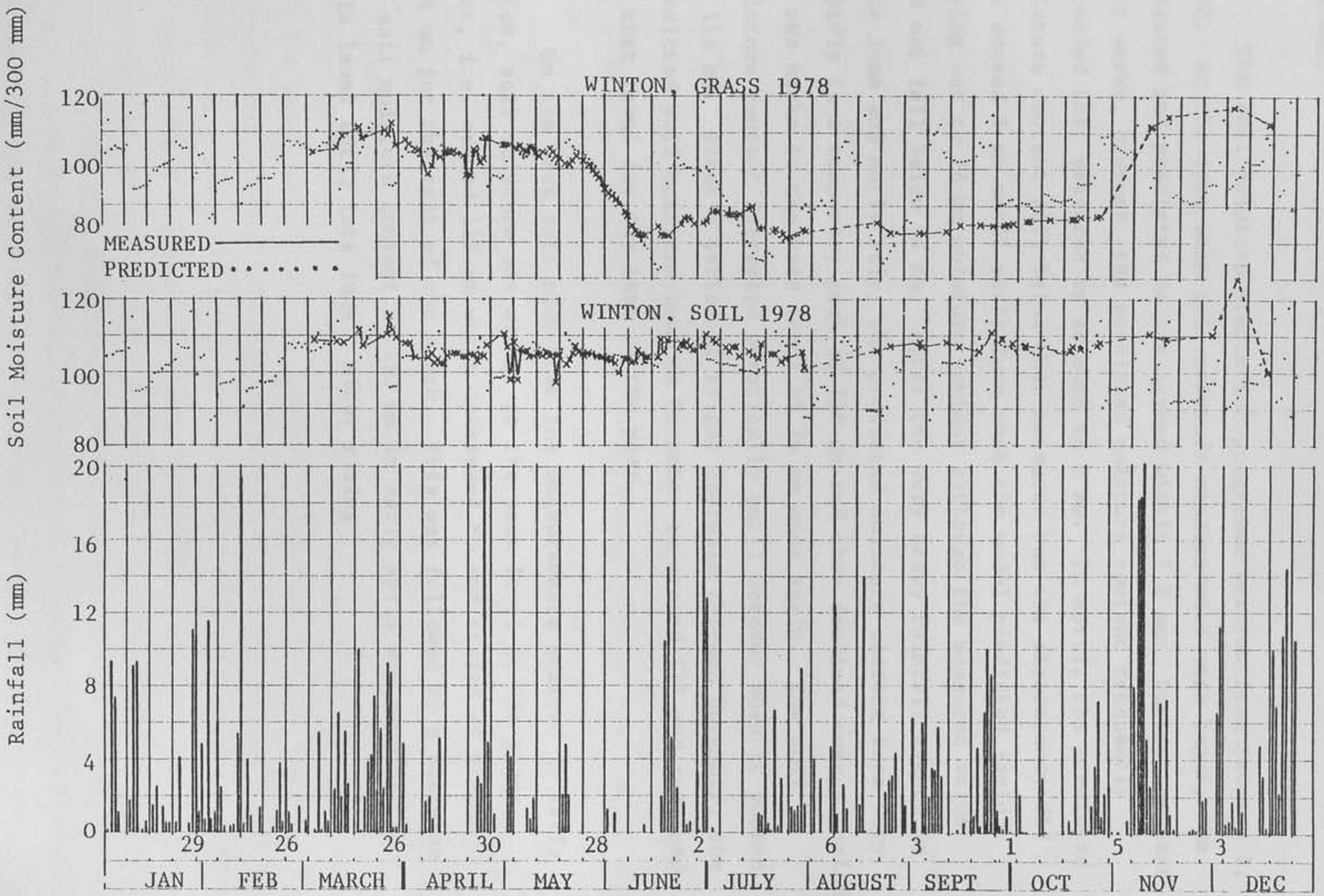

FIG. 7.6: Comparison of measured and predicted soil moisture content in the plough layer (300 mm) with grass cover and bare soil for Winton series in relation to precipitation during 1978

again declined steadily until a very wet period in the second week of November when it rose once more to fluctuate around the 115 mm moisture content.

The soil moisture prediction programme was run from January 1, 1978. At the date when soil moisture measurements were begun, the measured and predicted values agreed within ± 2 mm. During the next four weeks, however, the predicted moisture content frequently exceeded that measured by as much as 8 mm. In April, the predicted moisture content fell below that measured but the discrepancy did not exceed 5 mm until early June when the model predicted rapid drying out to 76 mm moisture content although the measured value did not fall below 94 mm. After the very heavy rainfall events in late June and early July, the predicted moisture content rose very rapidly to a temporary peak of 128 mm and then declined over a period of two weeks to the base level of 74 mm once again. The soil moisture content increased erratically until October when it peaked at 118 mm. After a period of slight decrease through November, the predicted soil moisture rose in November to around 115 and remained at that level for the rest of the year.

On the bare soil plot when the measurements started in early March, soil moisture was almost at the same level as the grass plot, i.e. around 112 mm which increased to and stayed at around 118 mm for the rest of the month. This was followed by a decrease in soil moisture content to 110 mm in early April and remained at this level until late June. After rising to a small peak of 116 mm at this date it returned to the previous level of 110 mm and fluctuated around this level until late September. The only drying out season occurred on the last week of September and only lasted for a week. On the first of November, soil reached its wettest point for the year at 120 mm and was followed by gradual drying to 110 mm. After a small rise, a rapid decline in the soil moisture content to its lowest value of 100 mm was achieved in early and late December.

The model was run from the first of January, 1978. From the day at which soil moisture measurements started, the predicted and measured soil moisture contents were in a very close agreement, except for four occasions on which a significant deviation occurred between measured and predicted values. First two occasions in which the moisture content was under-predicted were very similar to the grass plot but with a smaller magnitude. In the second two occasions, the model over-predicted the soil moisture content for mid-November and mid-December. These variations did not exceed 5 and 10 mm for the former and latter occasions, respectively.

For the Winton series on the grass plot, variation on both the predicted and measured values of soil moisture content was greater than their variations for the Macmerry series. The measurements started at the same date as two previous plots and soil moisture content at this point was 105 mm. Until the start of the drying season in the third week of May, the measured soil moisture content fluctuated around 98-110 mm. Soil reached to its driest level of 80 mm in the first week of June and fluctuated around 80-90 mm until late October. After a period of continued rainfall, the soil moisture content increased and agreement with the predicted values was improved throughout the wet period. The inconsistency between measured and predicted results on mainly dry periods, both in the preliminary and main test of the model is again attributed to the questionable reliability of the equipment. This idea can be substantiated by examining the actual results from tensiometers in Appendices C.1 & C.2. Throughout the dry periods, especially in the months of June and July when the soil dried beyond 30 cm Hg, either equipment failure occurred or considerable differences were noticed between the readings obtained from different pots at the same depth. This could be detected on 27 and 28th July for the former case and 18th July for the latter occasion when CEL 2 recorded 12.1 cm Hg. while CEL 1 and CEL 3 showed 34 and 40.4, respectively.

Another major discrepancy between measured and predicted soil moisture contents occurred towards the end of August and beginning of September, where after a fairly dry period and despite the fall of around 50 mm of rainfall, there was hardly any response on the measured values while the predicted values showed an appropriate rise in response to the rainfall. This could be attributed in the grass plot partly to interception by the vegetation and evaporating some of the rainfall before it reaches the soil and partly to the lateral drainage which may occur and then discharge the rainfall from the soil before it can reach to a level at which the tensiometer pot is installed. The excellent agreement between measured and predicted soil moisture content for the rest of the year in both soils under grass and bare soil, its constant response to rainfall and to drying in these periods, and its very simple data requirement justifies its use for prediction of soil moisture content for winter, spring and autumn seasons, i.e. the most critical season for ploughing and cultivation. The model can be tested for very dry seasons if a more reliable technique such as Neutron scattering method is available. Tensiometers were used in this study due to their simplicity and availability in order to obtain a trend in the fluctuation of soil moisture content. The drainage component of the model was tested separately and is described in the coming section.

7.2 Test of the Drainage Component of the Soil Moisture Model

The results obtained from the drainage experiment, 5.5, were plotted and the best curve was fitted for each soil (Figures 7.7 and 7.8). The following general equation was found to yield the best predicted results:

$$M = \frac{C_1}{DAY} + C_2 \qquad 7.3$$

where: M is the soil moisture content at the end of the day, DAY is the day number for which soil moisture content is being calculated and, C_1 and C_2 are constants which depend on type and moisture characteristics of the soil.

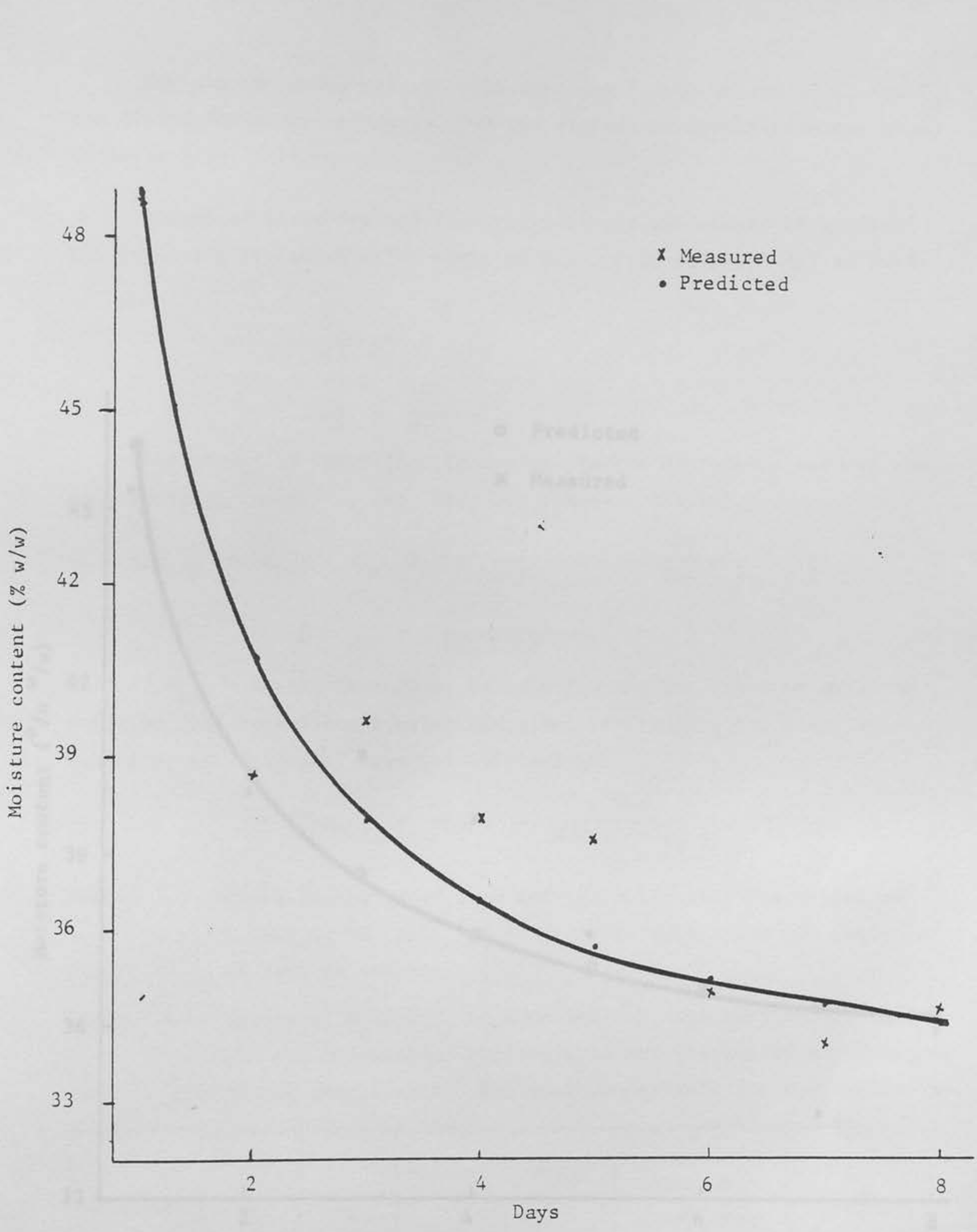

FIG. 7.7: Measured values of soil moisture content at different days after saturation, combined with predicted values using equation 7.3 and table 7.6 for Macmerry soil.

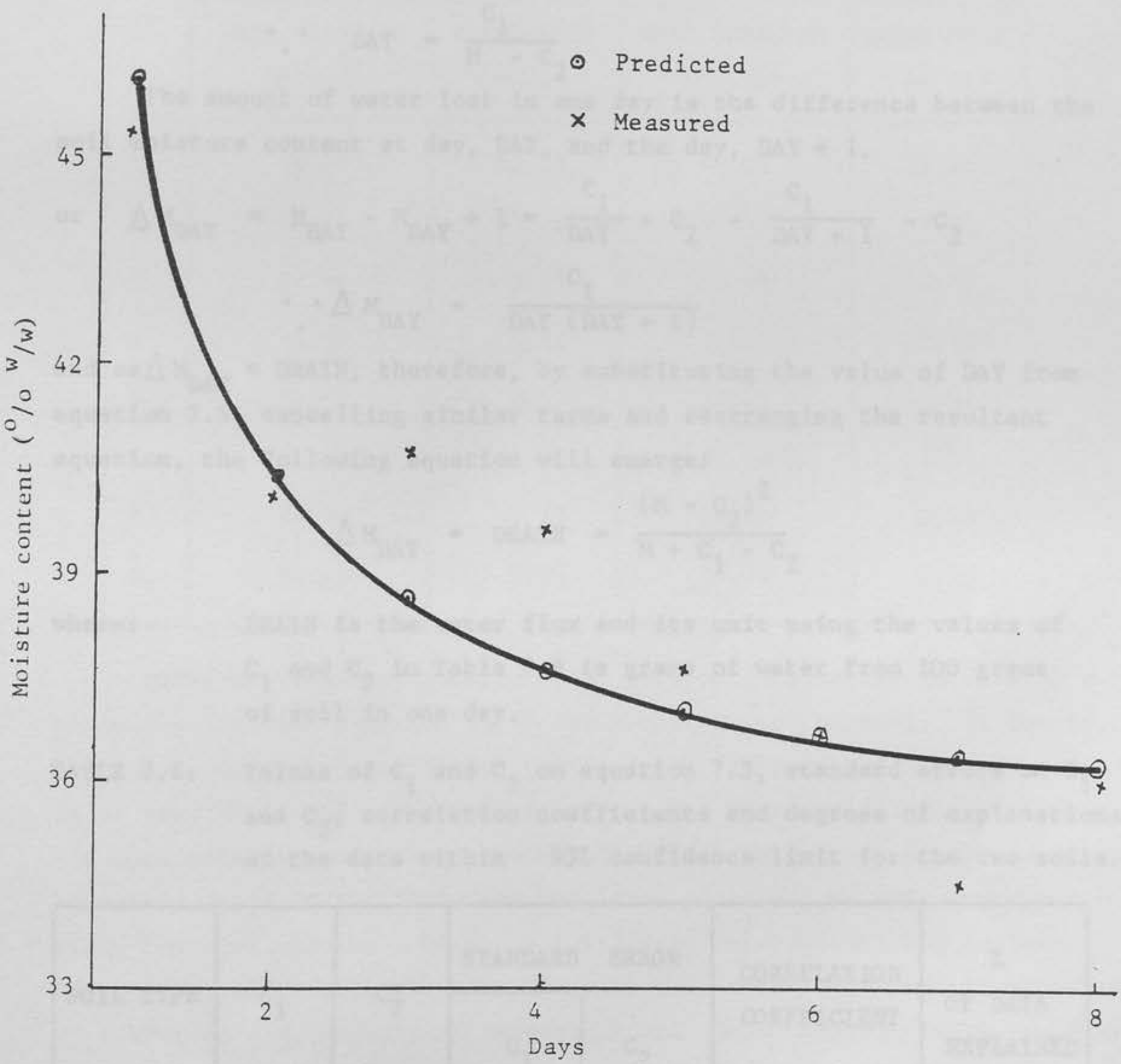

FIG. 7.8: Measured values of soil moisture content at different days after saturation combined with predicted values using equation 7.3 and table 7.6 for Winton soils.

For the two soils used in this experiment, the values of C_1 and C_2, the coefficients of correlation and the degrees of explanation are shown in Table 7.6.

Amount of water drained from the soil was calculated by means of the following procedure using equation 7.3. From equation 7.3 we have:

$$\frac{C_1}{DAY} = M - C_2 \qquad 7.4$$

$$\therefore \quad DAY = \frac{C_1}{M - C_2} \qquad 7.5$$

The amount of water lost in one day is the difference between the soil moisture content at day, DAY, and the day, DAY + 1.

$$\text{or} \quad \Delta M_{DAY} = M_{DAY} - M_{DAY} + 1 = \frac{C_1}{DAY} + C_2 - \frac{C_1}{DAY + 1} - C_2 \qquad 7.6$$

$$\therefore \Delta M_{DAY} = \frac{C_1}{DAY\,(DAY + 1)} \qquad 7.7$$

and as ΔM_{DAY} = DRAIN, therefore, by substituting the value of DAY from equation 7.5, cancelling similar terms and rearranging the resultant equation, the following equation will emerge:

$$\Delta M_{DAY} = DRAIN = \frac{(M - C_2)^2}{M + C_1 - C_2} \qquad 7.8$$

where: DRAIN is the water flux and its unit using the values of C_1 and C_2 in Table 7.6 is grams of water from 100 grams of soil in one day.

TABLE 7.6: Values of C_1 and C_2 on equation 7.5, standard errors on C_1 and C_2, correlation coefficients and degrees of explanations of the data within 95% confidence limit for the two soils.

SOIL TYPE	C_1	C_2	STANDARD ERROR		CORRELATION COEFFICIENT	% OF DATA EXPLAINED
			C_1	C_2		
MACMERRY	16.69	32.37	2.0747	0.9065	0.9567	91.52
WINTON	11.20	34.81	2.2883	0.9913	0.8958	80.24

The equation 7.8 and values of C_1 and C_2 from Table 7.6 were used and daily water flux in terms of mm/day from a 300 mm profile was calculated for Macmerry and Winton soils (Table 7.7 and Figure 7.9).

TABLE 7.7: Variation of soil water flux with varying soil moisture content for two different soils.

DAY	MACMERRY SOIL		WINTON SOIL	
	SOIL MOISTURE CONTENT % w/w	WATER FLUX mm/day	SOIL MOISTURE CONTENT % w/w	WATER FLUX mm/day
1	49.07	32.43	46.01	21.33
2	40.72	10.76	40.41	7.11
3	37.94	5.38	38.55	3.55
4	36.55	3.23	37.61	2.13
5	35.71	2.15	37.05	1.42
6	35.15	1.51	36.68	1.01
7	34.76	1.12	36.41	0.76
8	34.46	0.90	36.21	0.60

Different types of relationships were tried in order to develop a general predictive equation which has a theoretical backing. In theory, hydraulic conductivity and thus the drainage, is constant when the soil is at saturation and either ceases or reaches to a negligible value when the soil moisture content approaches the field capacity. Of the numerous equations examined the following two forms of equations were found to yield the best results. First, a log-linear relationship was assumed, (equation 4.44). This equation was then solved for upper and lower values of hydraulic conductivity at saturation and field capacity which resulted in equations 4.45. Values of daily water flux were predicted using this equation and compared with those obtained from the equation 7.8. Secondly, a log-log relationship in the following form was assumed:

$$\ln \mathrm{DRAIN}_n = C_1 \ln M_{n-1} + C_2 \qquad 7.9$$

and a regression analysis was carried out and a high correlation was obtained for two soils. The values of C_1 and C_2, standard error on C_1

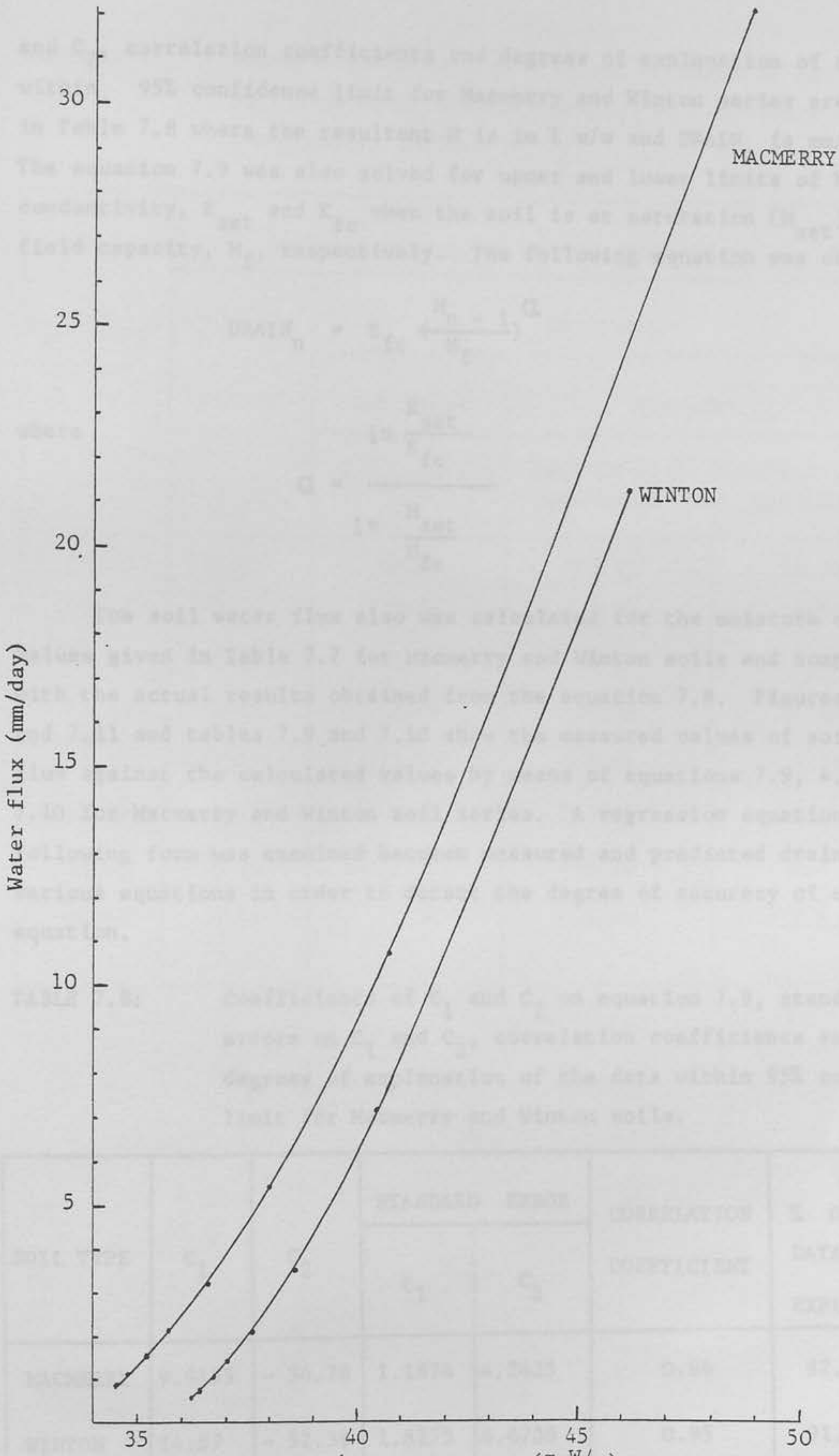

FIG. 7.9: Variations of soil water flux by changing soil moisture content.

and C_2, correlation coefficients and degrees of explanation of the data within 95% confidence limit for Macmerry and Winton series are given in Table 7.8 where the resultant M is in % w/w and $DRAIN_n$ is mm/day. The equation 7.9 was also solved for upper and lower limits of hydraulic conductivity, K_{sat} and K_{fc} when the soil is at saturation (M_{sat}) and at field capacity, M_f, respectively. The following equation was obtained:

$$DRAIN_n = K_{fc} \left(\frac{M_n - 1}{M_f}\right)^{\alpha} \qquad 7.10$$

where

$$\alpha = \frac{\ln \frac{K_{sat}}{K_{fc}}}{\ln \frac{M_{sat}}{M_{fc}}}$$

The soil water flux also was calculated for the moisture content values given in Table 7.7 for Macmerry and Winton soils and compared with the actual results obtained from the equation 7.8. Figures 7.10 and 7.11 and tables 7.9 and 7.10 show the measured values of soil water flux against the calculated values by means of equations 7.9, 4.45 and 7.10 for Macmerry and Winton soil series. A regression equation of the following form was examined between measured and predicted drainage from various equations in order to detect the degree of accuracy of each equation.

TABLE 7.8: Coefficients of C_1 and C_2 on equation 7.9, standard errors on C_1 and C_2, correlation coefficients and degrees of explanation of the data within 95% confidence limit for Macmerry and Winton soils.

SOIL TYPE	C_1	C_2	STANDARD ERROR		CORRELATION COEFFICIENT	% OF DATA EXPLAINED
			C_1	C_2		
MACMERRY	9.9155	- 34.78	1.1674	4.2425	0.96	92.32
WINTON	14.57	- 52.38	1.8275	6.6739	0.95	91.38

Equation 7.9 was also solved for upper and lower limits.

TABLE 7.9: Measured and predicted drainage by means of different equations at different levels of soil moisture content for Macmerry soils.

SOIL MOISTURE CONTENT % w/w	DRAINAGE FROM A 300 mm SOIL PROFILE mm/day			
	MEASURED	PREDICTED		
		EMPIRICAL	THEORETICAL	
		EQUATION 7.9	EQUATION 4.45 LOG-LINEAR	EQUATION 7.10 LOG-LOG
49.07	32.43	44.94	32.35	32.35
40.72	10.76	7.08	4.15	4.86
37.94	5.38	3.51	2.09	2.37
36.55	3.21	2.43	1.49	1.62
35.71	2.13	1.93	1.21	1.28
35.15	1.51	1.65	1.05	1.09
34.46	1.12	1.47	0.96	0.97
34.46	0.89	1.35	0.89	0.89

TABLE 7.10: Measured and predicted drainage by means of different equations at different levels of soil moisture content.

SOIL MOISTURE CONTENT % w/w	DRAINAGE FROM A 300 mm SOIL PROFILE mm/day			
	MEASURED	PREDICTED		
		EMPIRICAL	THEORETICAL	
		EQUATION 7.9	EQUATION 4.45 LOG-LINEAR	EQUATION 7.10 LOG-LOG
46.01	21.34	30.39	21.34	21.34
40.41	7.09	4.59	3.05	3.36
38.55	3.54	2.31	1.60	1.72
37.71	2.13	1.61	1.16	1.21
37.07	1.41	1.31	0.96	0.98
36.68	0.99	1.12	0.84	0.85
36.41	0.76	1.00	0.76	0.76
36.21	0.57	0.93	0.71	0.70

$$DRAIN_{PR} = C_1 \, DRAIN_{MR} + C_2 \qquad 7.10$$

where $DRAIN_{PR}$ is the predicted drainage;

$DRAIN_{MR}$ is the measured drainage;

C_1 and C_2 are coefficients.

Results of this analysis are given in tables 7.11 and 7.12 for Macmerry and Winton soil series, respectively.

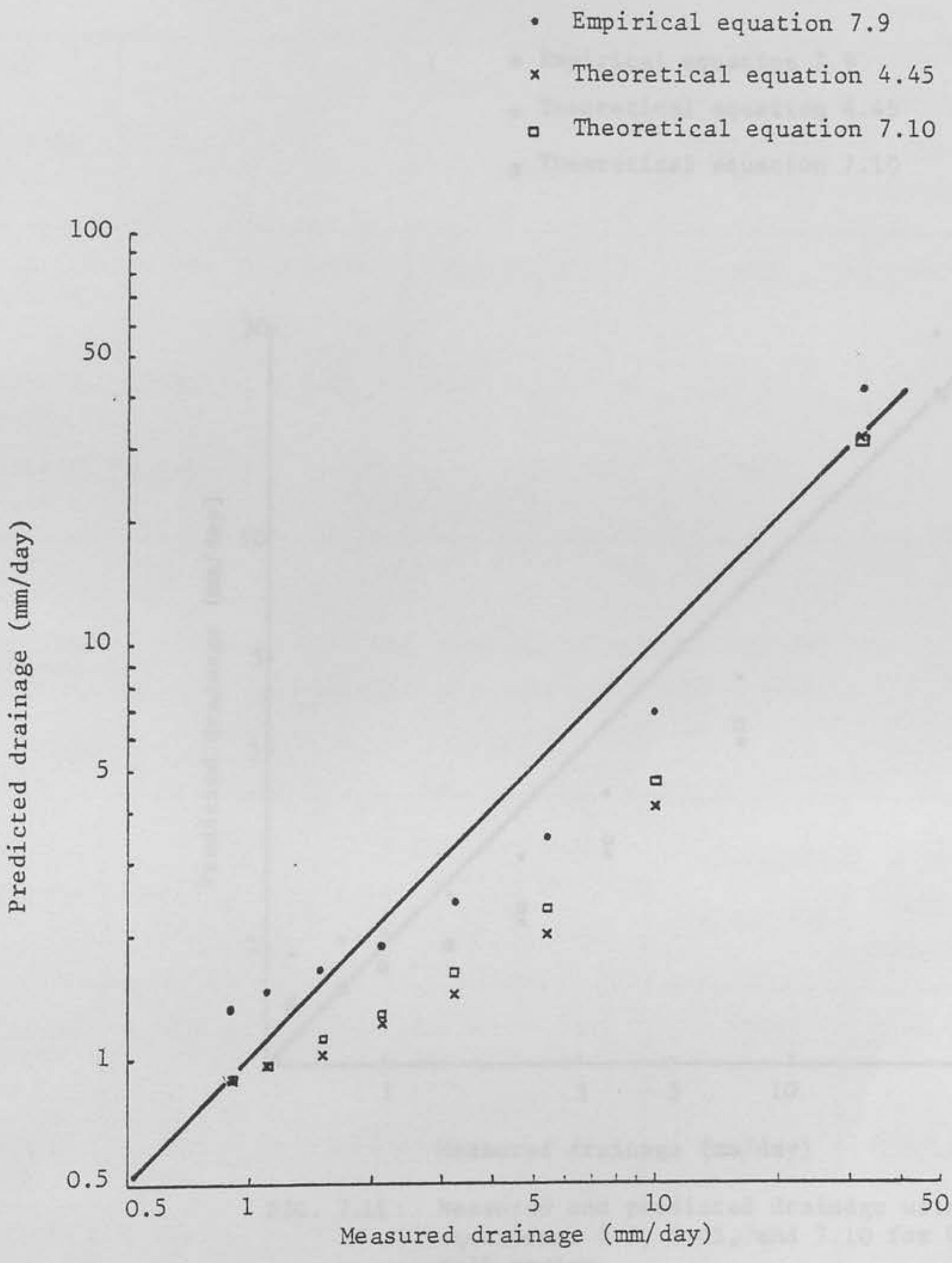

FIG. 7.10: Measured and predicted drainage using equations 7.9, 4.45 and 7.10 for Macmerry soil series.

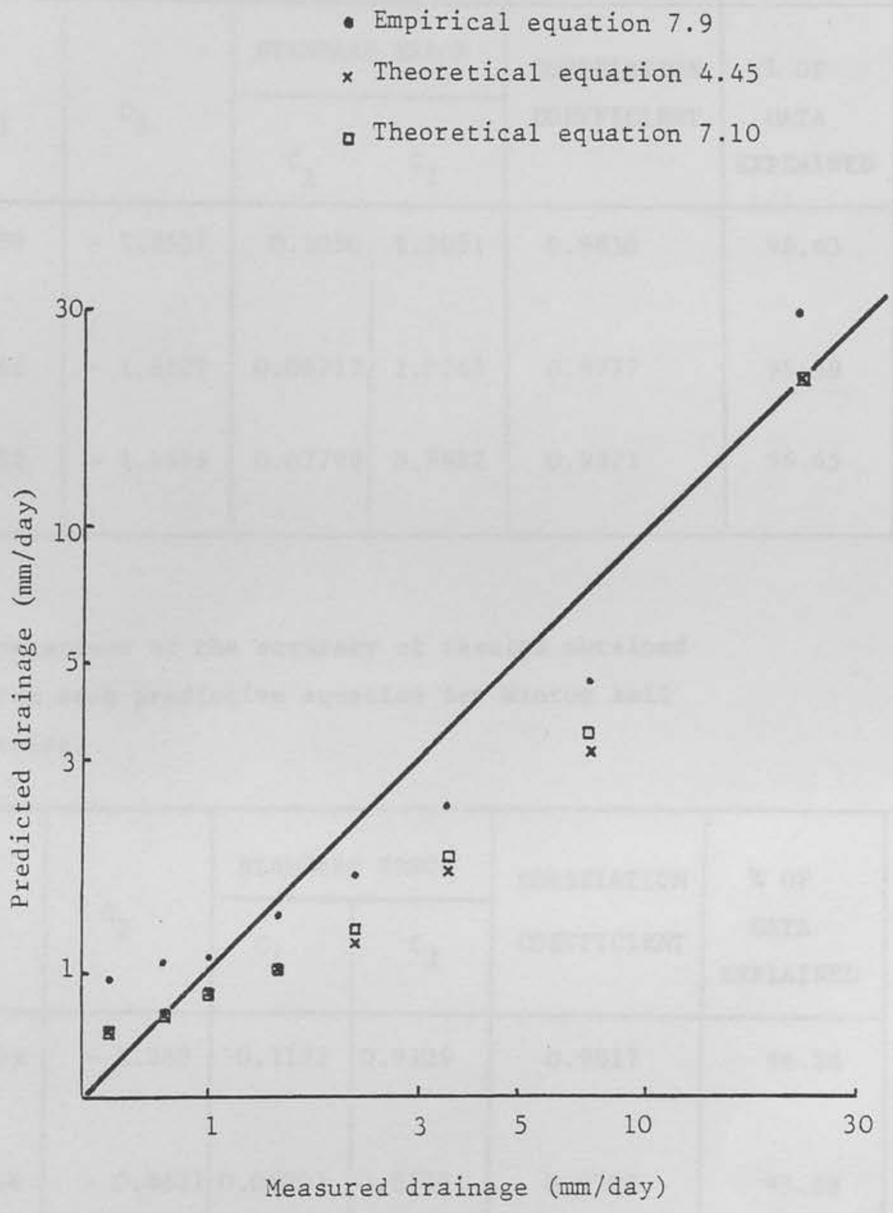

FIG. 7.11: Measured and predicted drainage using equations, 7.9, 4.45, and 7.10 for Winton soil series.

TABLE 7.11: Comparison of the accuracy of results obtained from each predictive equation for Macmerry soil series.

EQUATION	C_1	C_2	STANDARD ERROR		CORRELATION COEFFICIENT	% OF DATA EXPLAINED
			C_1	C_2		
EMPIRICAL EQUATION 7.9	1.3789	- 1.8537	0.1050	1.2951	0.9830	96.63
EQUATION 4.45	0.9941	- 1.6127	0.08717	1.0745	0.9777	95.59
EQUATION 7.10	0.9952	- 1.4656	0.07798	0.9612	0.9821	96.45

TABLE 7.12: Comparison of the accuracy of results obtained from each predictive equation for Winton soil series.

EQUATION	C_1	C_2	STANDARD ERROR		CORRELATION COEFFICIENT	% OF DATA EXPLAINED
			C_1	C_2		
EMPIRICAL EQUATION 7.9	1.4159	- 1.288	0.1122	0.9109	0.9817	96.36
EQUATION 4.45	0.9906	- 0.8821	0.08301	0.67351	0.9796	95.96
EQUATION 7.10	0.9918	-0.82205	0.07679	0.6230	0.9825	96.53

For both soil series, deviation of the slope of the regression line between predicted and measured data, C_1, from unity was considerably higher for equation 7.9 than it was for other two equations (Table 7.11 and 7.12). The intercept of C_2 and the standard errors for both C_1 and C_2 also had their highest value for this equation and had second and third lowest values for equations 4.45 and 7.10. Equation 7.10 had the highest and second highest coefficients of correlation for Winton and Macmerry soil series, respectively. From this analysis it can be concluded that the proposed theoretical equation, 7.10, has the higher degree of accuracy for the prediction of the soil water flux from homogeneous soils. The main advantage which the use of this equation has over the generally used empirical equations of type equation 7.9 is, that by the knowledge of very simple soil water properties which mainly are available in the literature, soil water flux can be estimated with reasonably high accuracy. In layered soils or in the presence of a low water table where the hydraulic gradient is less than unity, this equation can be used to estimate unsaturated hydraulic conductivity of soils from the saturated hydraulic conductivity. Equation 4.45 has been used in soil moisture predictions model so far but for future applications of the model it is proposed that equation 7.10 should be adopted.

7.3 Cone Index Results

It is widely accepted that the soil resistance to penetration of a cone penetrometer varies inversely with soil moisture content and is directly proportional to changes in soil bulk density, thus:

$$CI = C_1M^n + C_2V + C_3 \qquad 7.11$$

where: CI is cone index, MPa;
M is soil moisture content % w/w;
V is soil bulk density g/cm^3;
C_1 and C_2 are coefficients;
C_3 is constant;
n is an exponent.

The experimental data obtained from the field experiment 5.2 which are shown in Tables 5.7 - 5.9 and Figures 5.8 - 5.11, were analysed for each soil and in total to determine the values of coefficients and the exponent in equation 7.11 with the constraint that the constant C_3 must have a value of $\geqslant 0$ to conform with the established relationships for the cohesive strength of the soil. Furthermore when, C_3 is suppressed, a negative exponential value for n is required to ensure that C_1 is positive, thereby reconciling the positive contribution of the cohesive component of the cone index equation. The coefficient C_2 must always have a value of $\geqslant 0$.

With these restrictions in mind, a regression analysis of the data was done to obtain the best value for the exponent of n, and evaluate appropriate values for C_1 and C_2.

In addition, the data obtained by Woorhees and Walker (1977) was jointly analysed with experimental data assuming an average value of 16.7 kN/m^3 for the specific weight which was not identified. The soil specific weight was used as a measure of soil compaction instead of soil bulk density in this analysis. The standard error on the coefficients are represented by another term, T-STAT, which is calculated by dividing the coefficient by its standard error, therefore, the larger the T-STAT, the more accurate the regression coefficients.

Different values of the exponent, n, were examined ranging from -4 to -0.75 and their corresponding values for C_1 and C_2 were calculated for three soils individually, three soils together and three soils combined with the data obtained by Woorhees and Walker (1977), Table 7.13.

As the exponent became less negative, for Macmerry soils series, the coefficient C_1 decreased while the T-STAT on this coefficient and correlation (degree of explanation) increased marginally. The coefficient C_2 and its T-STAT fell more rapidly so that they became negative when the exponent approached -0.75.

A similar trend occurred for the Winton series except that the negative C_2 was obtained when n reached -1.

For Darvel soils, the T-STAT on C_1 and the correlation coefficient also declined as well as C_1, C_2 and the T-STAT on C_2. The negative value of C_2 was obtained at n = -1.25. When the data for all three soils were analysed together, the correlation coefficient declined from around 98% to around 97% and its trend changed, i.e. instead of steady increase or decrease as in the previous cases, the correlation coefficient increased to its maximum value of 97.70% when n = -2 and started to decline beyond this point. This trend was similar for the T-STAT on C_1 but C_1, C_2 and the T-STAT on C_2 declined steadily so that a negative C_2 occurred at n = -1.25. From these results, it was found that the exponent -2, gave the maximum explanation and accuracy for all soils together and optimum

TABLE 7.13: Values of C_1 and C_2, T-STAT on C_1 and C_2 and degrees of explanation for varying values of the exponent, n, in three different soils combined with data obtained by Woorhees and Walker (1977).

	MACMERRY			DARVEL			WINTON			ALL SOILS			ALL SOILS & WOORHEES DATA		
EXPONENT	C_1 (T-STAT)	C_2 (T-STAT)	EXPL. %	C_1 (T-STAT)	C_2 (T-STAT)	EXPL. %	C_1 (T-STAT)	C_2 (T-STAT)	EXPL. %	C_1 (T-STAT)	C_2 (T-STAT)	EXPL. %	C_1 (T-STAT)	C_2 (T-STAT)	EXPL. %
-4	92424 (2.26)	0.0595 (9.57)	98.44	161235 (5.31)	0.3827 (9.15)	98.28	178043 (3.51)	0.0376 (9.04)	98.17	179544 (8.02)	0.0408 (13.95)	97.55	269484 (9.48)	0.0255 (5.81)	92.98
-3.75	44223 (2.31)	0.0583 (8.84)	98.45	74453 (5.30)	0.0370 (8.46)	98.28	79882 (3.54)	0.03681 (8.48)	98.19	83504 (8.11)	0.0394 (12.86)	97.58	128245 (9.50)	0.0228 (4.90)	93.00
-3.50	21245 (2.35)	0.0569 (8.09)	98.47	34508 (5.30)	0.357 (7.73)	98.28	36969 (3.58)	0.0358 (7.85)	98.20	38956 (8.20)	0.0377 (11.72)	97.61	61251 (9.53)	0.0196 (3.98)	93.01
-3.25	10255 (2.40)	0.0553 (7.34)	98.48	16064 (5.29)	0.0317 (6.96)	98.27	16265 (3.62)	0.0347 (7.21)	98.22	18240 (8.28)	0.0358 (10.52)	97.63	29376 (9.54)	0.0160 (3.03)	93.02
-3.00	4978 (2.45)	0.0535 (6.57)	98.49	7517 (5.28)	0.0323 (6.17)	98.27	7392 (3.66)	0.0333 (6.54)	98.23	8579 (8.35)	0.0336 (9.27)	97.65	14156 (9.55)	0.0118 (2.07)	93.03
-2.75	2433 (2.50)	0.0513 (5.99)	98.50	3539 (5.26)	0.0301 (5.35)	98,27	3380 (3.70)	0.0318 (5.84)	98.25	4057 (4.41)	0.0310 (7.97)	97.67	6859 (9.55)	0.0068 (1.10)	93.03
-2.50	1198 (2.55)	0.0486 (5.01)	98.51	1679 (5.25)	0.0275 (4.50)	98.26	1557 (3.74)	0.0299 (5.10)	98.27	1931 (8.46)	0.0279 (6.61)	97.68	3344 (9.53)	0.00092 (0.14)	93.01
-2.25	598.86 (2.60)	0.0453 (4.21)	98.53	803.93 (5.23)	0.0243 (3.62)	98.25	724.65 (3.78)	0.0278 (4.33)	98.28	927.82 (8.49)	0.0241 (5.21)	97.69	1640 (9.47)	-0.0061 (-0.81)	92.97
-2.00	300.94 (2.66)	0.04120 (3.41)	98.54	389.42 (5.21)	0.0203 (2.71)	98.25	341.09 (3.82)	0.0248 (3.52)	98.30	450.46 (8.50)	0.0194 (3.77)	97.70	809.25 (9.33)	-0.014 (-1.70)	92.87
-1.75	154.24 (2.72)	0.0358 (2.60)	98.56	191.46 (5.19)	0.0151 (1.79)	98.24	163.04 (3.87)	0.0211 (2.67)	98.32	221.82 (8.47)	0.0134 (2.30)	97.69	400.08 (9.07)	-0.024 (-2.46)	92.68
-1.50	80.79 (2.79)	0.0285 (1.78)	98.58	96.01 (5.17)	0.082 (0.84)	98.23	79.53 (3.93)	0.0161 (1.79)	98.34	111.32 (8.41)	0.0055 (0.81)	97.67	196.46 (8.59)	-0.034 (-2.99)	92.30
-1.25	43.60 (2.87)	0.0181 (0.98)	98.60	49.48 (5.14)	-0.0013 (-0.12)	98.22	39.90 (3.99)	0.0092 (0.87)	98.37	57.33 (8.28)	-0.0055 (-0.67)	97.63	93.69 (7.73)	-0.0430 (-3.10)	91.60
-1.00	24.56 (2.97)	0.0024 (0.10)	98.62	26.53 (5.11)	-0.015 (-1.09)	98.20	20.84 (4.07)	-0.0127 (-0.10)	98.40	30.63 (8.04)	-0.0218 (-2.08)	97.58	41.25 (6.37)	-0.0435 (-2.58)	90.38
-0.75	19.77 (3.10)	-0.023 (-0.77)	98.66	15.16 (5.07)	-0.0400 (-2.06)	98.19	11.59 (4.16)	-0.0186 (-1.11)	98.43	17.25 (7.55)	-0.0479 (-3.28)	97.40	15.18 (4.52)	-0.026 (-1.33)	88.68

explanation and accuracy for individual soils. The following equations are the final forms of the equations which explained the maximum amount of data points and resulted in the most accurate prediction of the cone indices for each of the three soils:

for Macmerry series;

$$CI = 300.93\ M^{-2} + 0.0412\ \gamma \tag{7.12}$$

for Darvel series;

$$CI = 389.42\ M^{-2} + 0.0203\ \gamma \tag{7.13}$$

and for Winton series;

$$CI = 341.09\ M^{-2} + 0.0248\ \gamma \tag{7.14}$$

Despite the variations in the coefficient values for the different soils, the simplicity of adopting a general equation outweighed the minor loss of accuracy incurred. The general equation:

$$CI = 450.46\ M^{-2} + 0.0194\ \gamma \tag{7.15}$$

where: CI is the cone index MPa;

M is the moisture content % w/w;

γ is the specific weight kN/m^3, explained 97.70% of the data while individual equations explained 98.25, 98.24 and 98.30% of the data for Macmerry, Darvel and Winton soil, respectively (Table 7.13).

When the data obtained by Woorhees and Walker (1977) was added to the experimental data, a considerable decline was noticed in the degree of explanation but the trend was similar to the general equation peaking at n = -3 with relatively lower dependence on soil specific weight. The resultant equation is:

$$CI = 14156\ M^{-3} + 0.0118\ \gamma \tag{7.16}$$

which explained 93.03% of the data. These data have been recorded for a soil moisture content range of 20-30% and experimental data extended this range to around 45% (Figure 5.11).

Cone indices were calculated for each soil, N.I.A.E. field data, and the data obtained from the plough draught experiment using the specific equations, the general equation and the equation fitted to the data including the ones obtained by Woorhees and Walker (1977).

These results are given in Tables 7.14 - 7.16 for the three soils of Darvel, Macmerry and Winton.

For Macmerry soils all the data were predicted within ±25% using the specific equation 7.12 and a correlation coefficient of 0.90 was obtained between predicted and measured data (figure 7.12). When the general equation 7.15 was used to calculate cone indices this accuracy was increased for lower values of cone index but slightly deteriorated for higher cone indices (figure 7.13), the correlation coefficient between the predicted and measured values of the cone index was 0.77. Using equation 7.16 to predict cone indices for Darvel soils, a much closer prediction was made and a high correlation coefficient (0.93) was obtained (figure 7.14). For Darvel soils, the accuracy was similar (0.91) when prediction was made using specific equation 7.13 (figure 7.15) and general equation 7.15 (figure 7.13) but was poorest when equation 7.16 was used.

For Winton soil accuracy was improved from 0.90 to 0.93 when the general equation was used instead of the specific equation (figure 7.16) for that soil. The use of equation 7.16 resulted in a considerable decline in accuracy (0.70) and an under prediction (figure 7.14). A better prediction was made when cone index was predicted by means of equation 7.16 instead of the equation 7.15 for the data obtained by Woorhees and Walker (1977), figure 7.14 and table 7.17. An over prediction of some 40% was obtained when a comparison was made between the average field cone indices for a depth of 230 mm associated with the N.I.A.E. plough draught studies (Gee-Clough et al, 1978) and predicted value (figure 7.17). This level of over prediction is similar to that obtained in the plough draught experiment (5.1) when average cone indices were used instead of cone indices at the median depth. Neither of the equations obtained from this analysis were able to explain the disparity of the exceptionally high cone indices obtained for reconstituted soils in the soil moisture range of

TABLE 7.14: Measured values of cone indices compared with predicted values by means of different equations for Macmerry soil at Longrig.

	MEASURED	CALCULATED FROM SPECIFIC EQUATION		CALCULATED FROM GENERAL EQUATION		CALCULATED FROM EQUATION 7.16	
REF	CONE INDEX MPa	CONE INDEX MPa	S.D.	CONE INDEX MPa	S.D.	CONE INDEX MPa	S.D.
1	1.0618	1.0302	0.26	0.9962	0.53	1.1037	- 0.16
2	0.7308	0.9034	- 1.46	0.8064	- 0.62	0.7643	- 0.13
3	0.9101	1.0100	- 0.85	0.9669	- 0.46	1.0480	- 0.54
4	0.8342	0.8854	- 0.43	0.7794	0.45	0.7202	0.45
5	0.8687	1.0974	- 1.93	1.0968	- 1.87	1.3028	- 1.72
6	1.1652	0.9463	1.85	0.8764	2.37	0.8866	1.10
7	0.7515	0.8901	- 1.17	0.7923	- 0.33	0.7438	0.03
8	1.0342	1.0424	- 0.07	1.0203	0.11	1.1538	- 0.47
9	0.8480	0.8557	- 0.06	0.7408	0.88	0.6616	0.73
10	0.9653	0.8944	0.60	0.7987	1.37	0.7544	0.83
11	1.1997	0.9753	1.90	0.9148	2.34	0.9525	0.98
12	0.7308	0.8599	- 1.09	0.7421	- 0.09	0.6614	0.27
13	1.0618	0.9527	0.92	0.8810	1.48	0.8921	0.67
14	0.8825	0.9756	- 0.78	0.9153	- 0.26	0.9534	- 0.28
15	0.8411	0.8401	0.009	0.7124	1.05	0.6160	0.89
16	1.1169	0.9365	1.53	0.8766	1.97	0.8949	0.88
17	0.8274	0.8706	- 0.36	0.7779	0.40	0.7274	0.39
18	1.0411	0.9195	1.03	0.8512	1.56	0.8505	0.75
19	0.8894	0.9004	- 0.09	0.8227	0.54	0.8016	0.34
20	0.8549	0.8745	- 0.16	0.7839	0.58	0.7372	0.46
21	0.9895	0.9206	0.55	0.8486	1.12	0.8439	0.56
22	0.8136	0.8556	- 0.35	0.7515	0.51	0.6831	0.51
23	0.9653	0.9983	- 0.28	0.9650	0.002	1.0542	- 0.35
24	0.9721	0.886	0.70	0.8007	1.14	0.7629	0.82
25	0.8549	0.8714	- 0.14	0.7751	0.65	0.7209	0.53

TABLE 7.15: Measured values of cone indices compared with predicted values by means of different equations for Darvel soil at Plover Hall.

REF	MEASURED	CALCULATED FROM SPECIFIC EQUATION		CALCULATED FROM GENERAL EQUATION		CALCULATED FROM EQUATION 7.16	
	CONE INDEX MPa	CONE INDEX MPa	S.D.	CONE INDEX MPa	S.D.	CONE INDEX MPa	S.D.
1	0.5584	0.7623	-1.99	0.8322	-2.25	0.8218	-1.04
2	0.6826	0.8204	-1.35	0.8994	-1.78	0.9401	-1.02
3	0.5171	0.6060	-0.87	0.6513	-1.10	0.5373	-0.08
4	0.5240	0.5412	-0.16	0.5764	-0.43	0.4354	0.35
5	0.5309	0.5771	-0.45	0.6180	-0.71	0.4909	0.15
6	0.5860	0.6606	-0.73	0.7146	-1.05	0.6311	-0.17
7	0.8687	0.7162	1.49	0.7789	-0.73	0.7330	0.53
8	0.7791	0.8627	-0.82	0.9484	-1.39	1.0304	-0.99
9	0.8061	0.7799	0.26	0.8525	-0.37	0.8569	-0.19
10	0.8894	0.8688	0.20	0.9554	-0.54	1.0432	-0.61
11	0.5860	0.6526	-0.65	0.7053	-0.98	0.6168	-0.12
12	0.5722	0.5871	-0.14	0.6295	-0.47	0.5066	0.26
13	0.5653	0.5841	-0.18	0.6259	-0.49	0.5010	0.25
14	0.6757	0.6629	0.12	0.7171	-0.34	0.6340	0.16
15	0.9790	0.9172	0.60	1.0112	-0.26	1.1491	-0.67
16	0.8618	0.8126	0.48	0.8902	-0.23	0.9226	-0.24
17	0.8274	0.8448	-0.17	0.9275	-0.82	0.9905	-0.64
18	0.9997	0.8411	1.55	0.9232	0.62	0.9829	0.06
19	0.7929	0.6236	1.66	0.6716	0.99	0.5663	0.89
20	0.6757	0.5585	1.15	0.5963	0.65	0.4612	-0.85

TABLE 7.16: Measured values of cone indices compared with predicted values by means of different equations for Wintons soils at House Field.

REF	MEASURED	CALCULATED FROM SPECIFIC EQUATION		CALCULATED FROM GENERAL EQUATION		CALCULATED FROM EQUATION 7.16	
	CONE INDEX MPa	CONE INDEX MPa	S.D.	CONE INDEX MPa	S.D.	CONE INDEX MPa	S.D.
1	0.6550	0.7464	-1.06	0.8236	-1.38	0.8086	-0.60
2	0.6067	0.7083	-1.18	0.7733	-1.37	0.7250	-0.46
3	0.4068	0.6134	-2.40	0.6480	-1.98	0.5336	-0.50
4	0.3516	0.5015	-1.74	0.5002	-1.22	0.3435	0.03
5	0.5722	0.5791	-0.08	0.6079	-0.29	0.4838	0.35
6	0.7101	0.6805	0.34	0.7418	-0.26	0.6819	0.11
7	0.6272	0.6279	-0.006	0.6424	-0.37	0.5754	0.20
8	0.4895	0.5178	-0.33	0.5269	-0.30	0.3793	0.43
9	0.5378	0.4929	0.52	0.4957	0.34	0.3438	0.76
10	0.6343	0.6404	-0.07	0.6906	-0.46	0.6048	0.11
11	0.7653	0.6375	1.48	0.6867	0.64	0.5991	0.65
12	0.5998	0.5636	0.42	0.5891	0.08	0.4602	0.55
13	0.6412	0.6029	0.44	0.6309	0.08	0.5058	0.53
14	0.7308	0.6986	0.37	0.7573	-0.21	0.6944	0.14
15	0.6688	0.6890	-0.23	0.7446	-0.62	0.6743	-0.02
16	0.5447	0.5420	0.031	0.5505	-0.04	0.4004	0.57
17	0.5791	0.4900	1.03	0.4867	0.78	0.3296	0.98
18	0.7032	0.6230	0.93	0.6624	0.33	0.5564	0.58
19	0.7222	0.7032	0.80	0.7683	0.03	0.7193	0.21
20	0.7032	0.6311	0.84	0.6731	0.24	0.5721	0.52

TABLE 7.17: Measured cone index values at different levels of soil moisture content compared with the predicted ones (Woorhees and Walker, 1977).

REF	SOIL MOISTURE CONTENT % $^{w}/w$	CONE INDEX MPa		STANDARD DEVIATION
		MEASURED	PREDICTED	
1	21.58	0.19995	1.60564	-1.254
2	21.58	1.37900	1.60564	-0.989
3	21.60	1.75133	1.60173	o.593
4	22.00	1.35142	1.52650	-0.694
5	22.20	0.99977	1.49088	-1.947
6	22.25	1.64790	1.48218	0.657
7	22.45	1.64790	1.44814	0.792
8	22.45	1.93060	1.44814	1.912
9	23.13	2.11676	1.34100	3.075
10	23.47	1.93060	1.29199	2.531
11	23.47	1.17215	1.29199	-0.475
12	24.82	0.97909	1.12285	-0.570
13	25.30	0.84808	1.07115	-0.884
14	25.50	0.59986	1.05074	-1.787
15	25.50	0.79982	1.05074	-0.995
16	25.41	1.17904	1.05984	0.472
17	26.10	0.93772	0.99320	-0.220
18	26.50	0.65502	0.95768	-1.200
19	26.73	1.15146	0.93822	0.845
20	27.00	0.75155	0.91620	-0.653
21	27.30	0.64813	0.89275	-0.970
22	27.50	0.59986	0.87768	-1.101
23	27.55	0.37922	0.87398	-1.961
24	28.30	0.24822	0.82156	-2.273
25	28.00	0.57918	0.84186	-1.041
26	28.30	0.55849	0.82156	-1.043
27	28.60	0.89635	0.80211	0.374
28	28.90	0.59986	0.78346	-0.728
29	29.50	0.19995	0.74840	-2.174

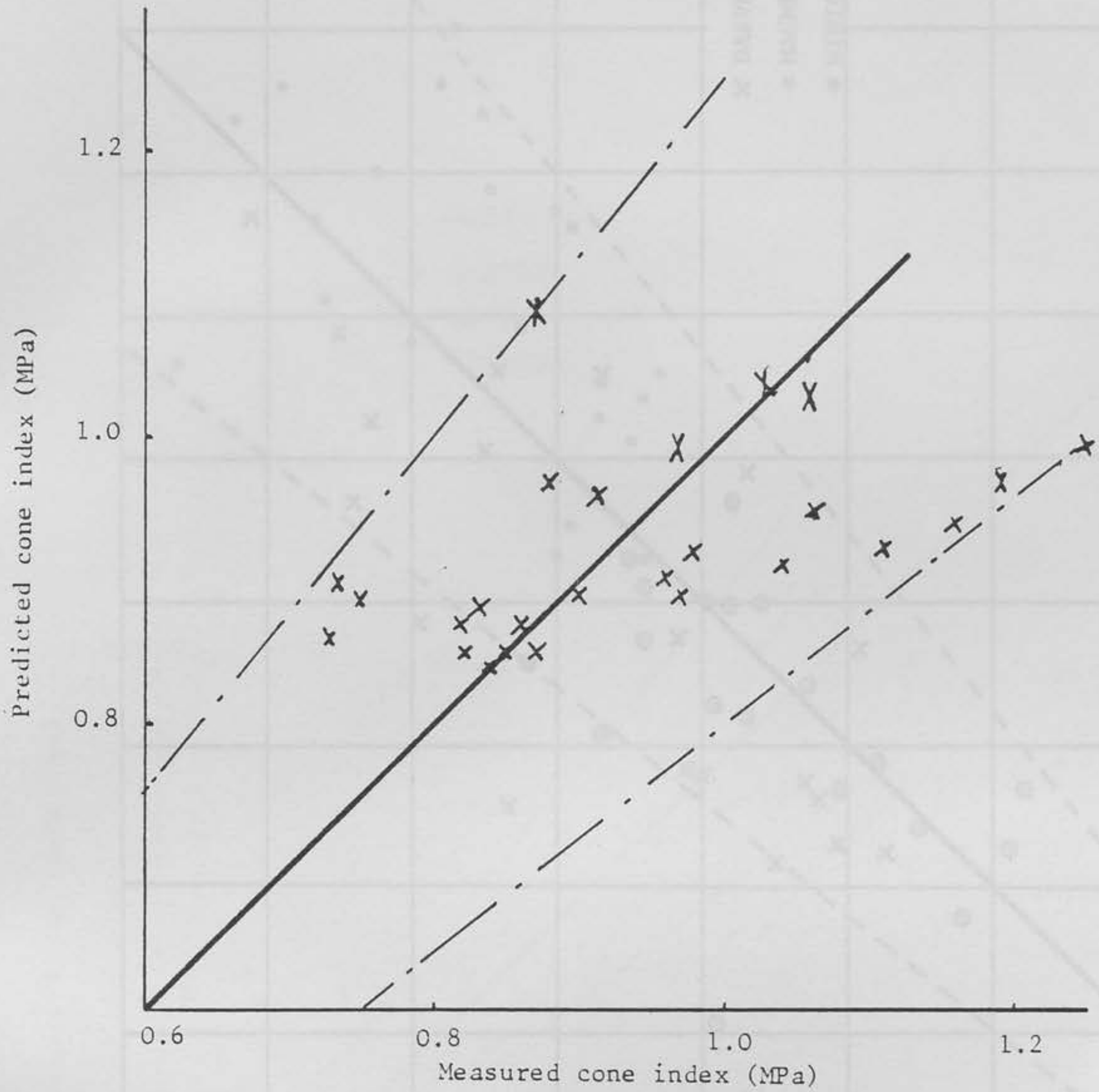

FIG. 7.12: Measured and predicted values of cone indices for Macmerry soil at Longrig by means of specific equation 7.12.

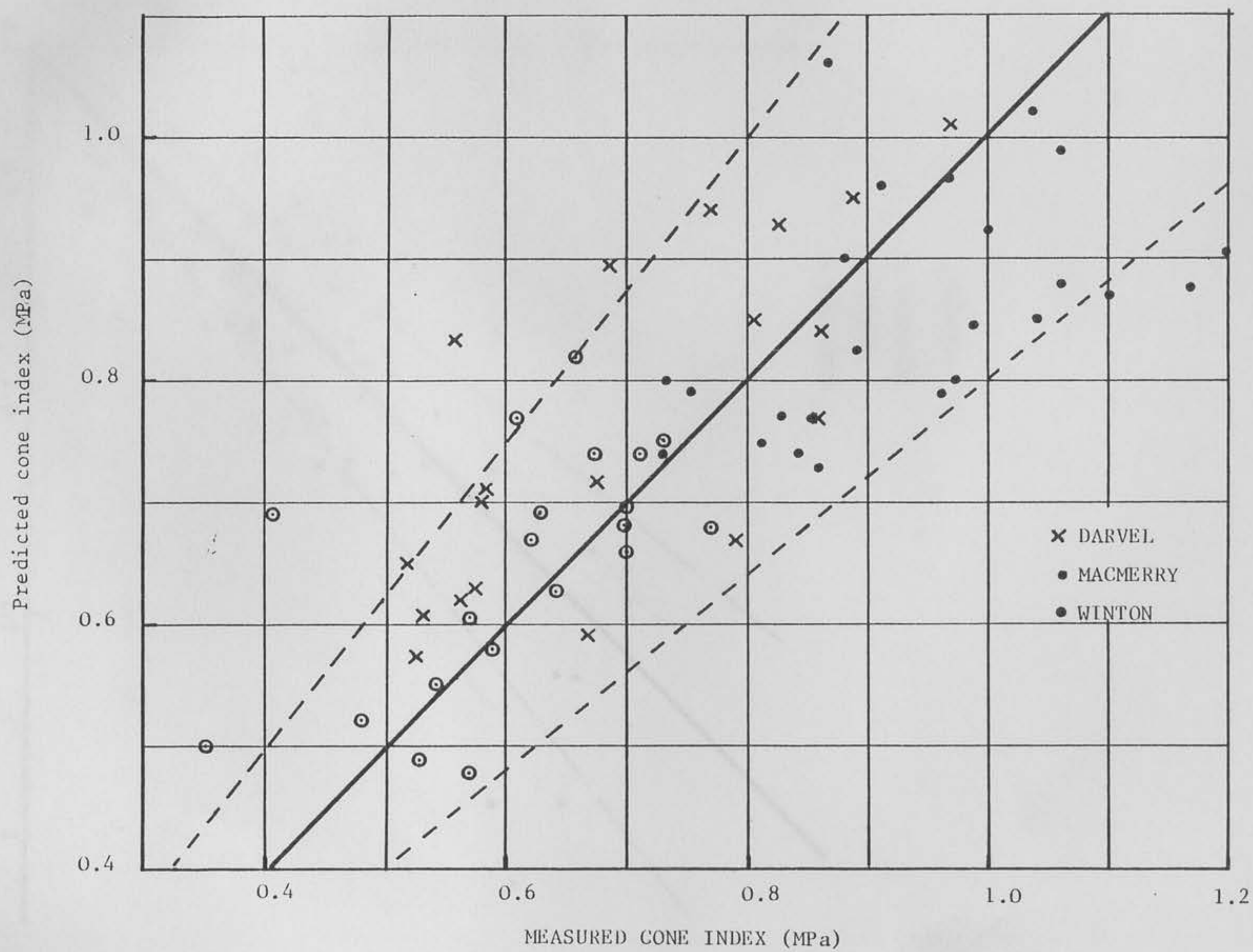

FIG. 7.13: Measured and predicted values of cone indices for three soil series of Darvel, Macmerry and Winton using equation 7.15.

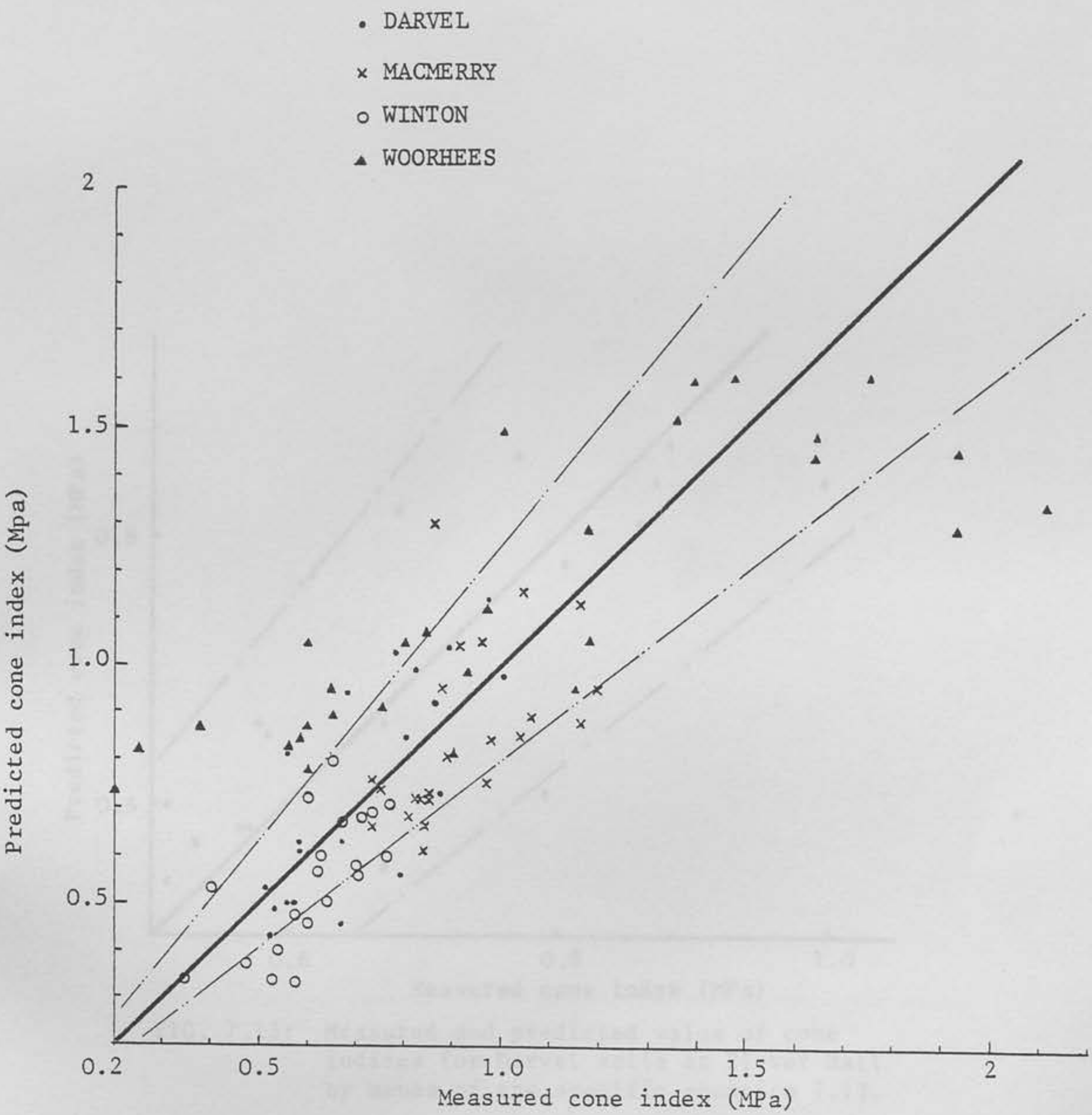

FIG. 7.14: Measured and predicted values of cone index for different soils and data obtained by Woorhees and Walker (1978) by means of equation 7.16.

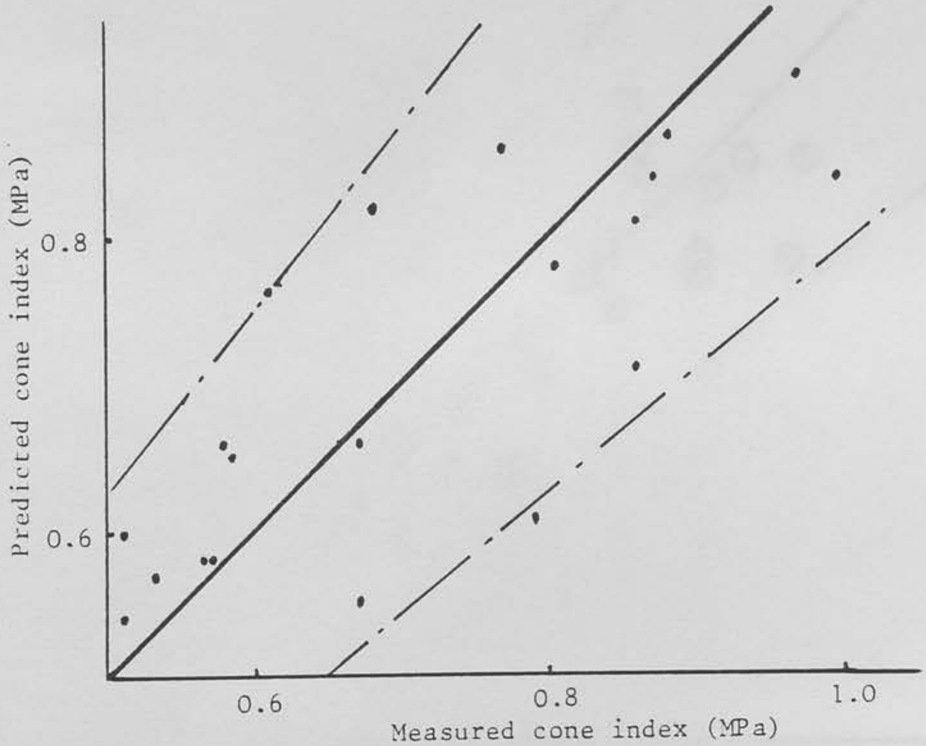

FIG. 7.15: Measured and predicted value of cone indices for Darvel soils at Plover Hall by menas of the specific equation 7.13.

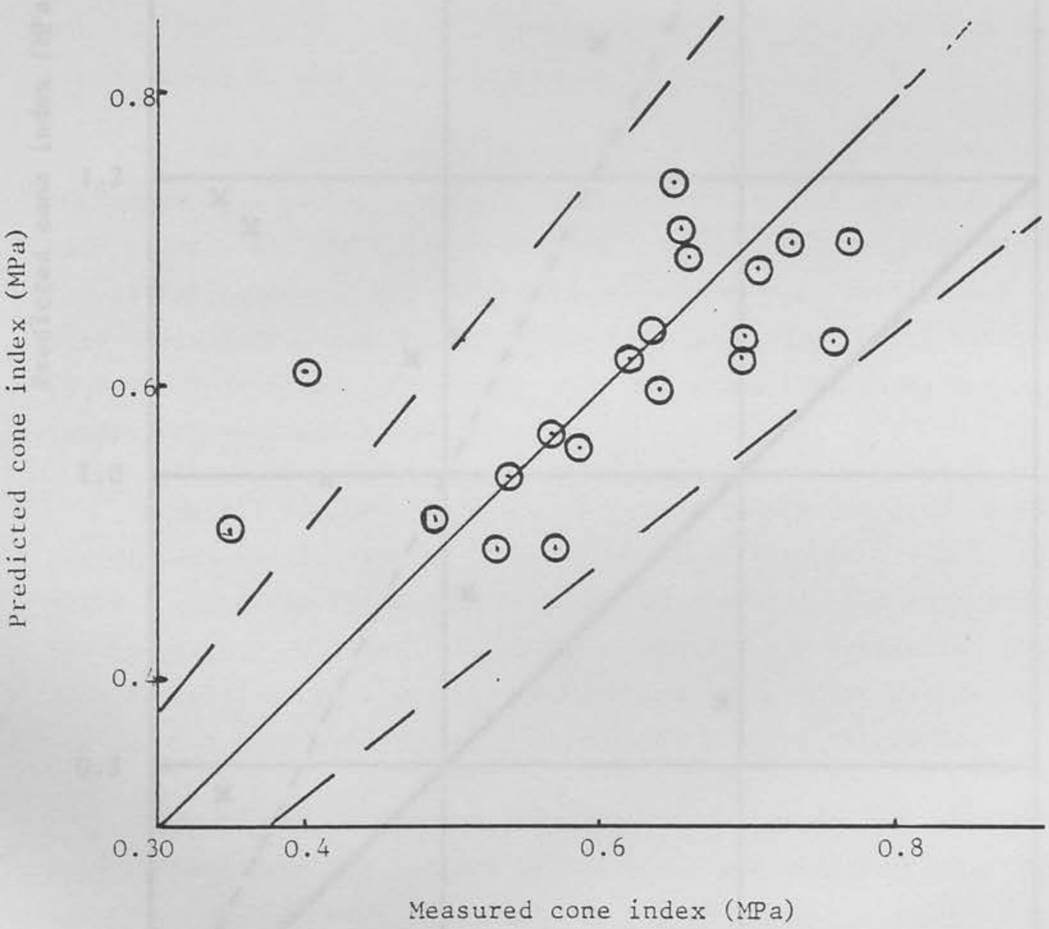

FIG. 7.16: Measured and predicted values of cone indices for Winton soils at House Field by means of specific equation 7.14.

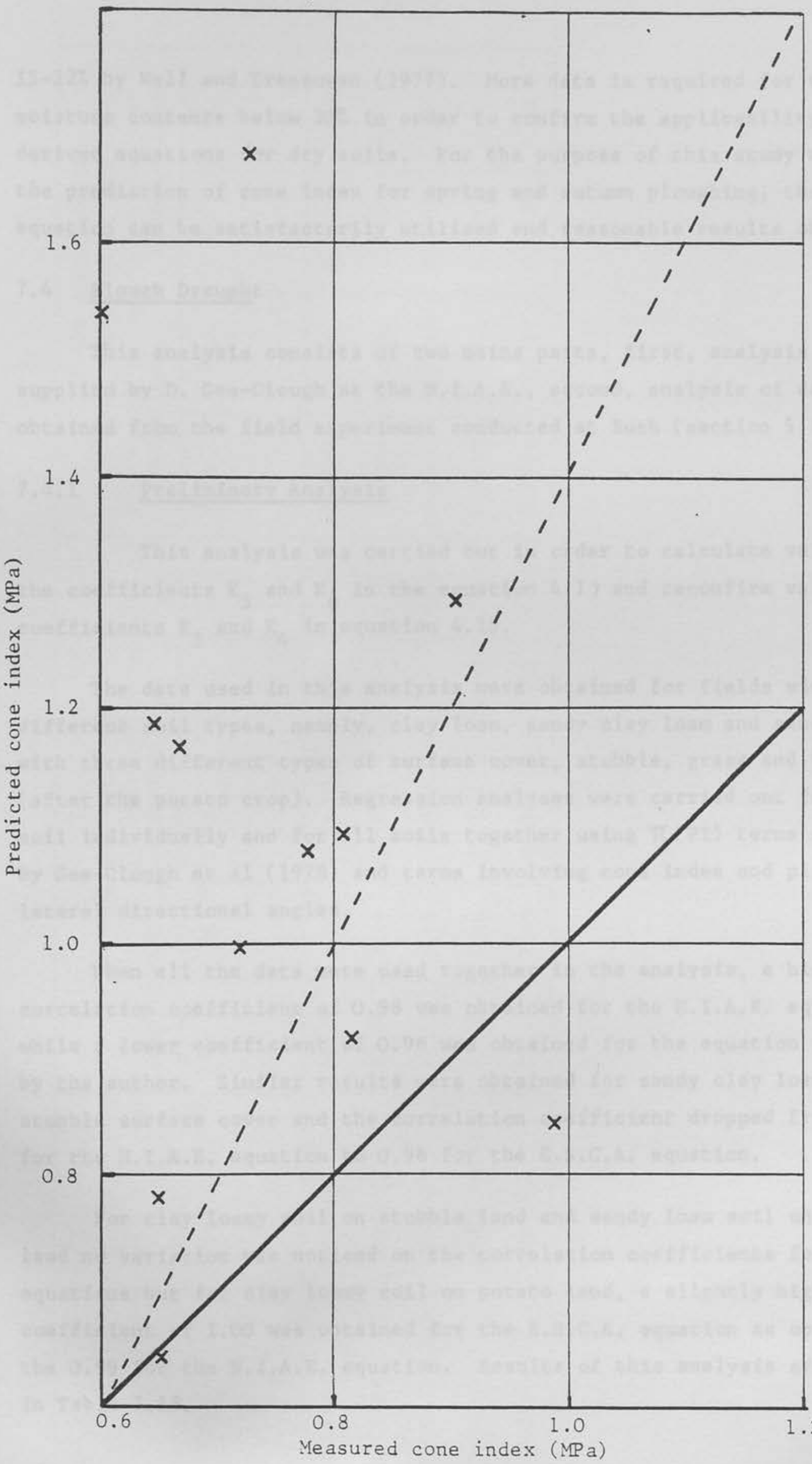

FIG. 7.17: Measured and predicted values of cone index for N.I.A.E. field data using equ. 7.15

15-22% by Well and Treesuwan (1977). More data is required for the soil moisture contents below 20% in order to confirm the applicability of derived equations for dry soils. For the purpose of this study which is the prediction of cone index for spring and autumn ploughing, the general equation can be satisfactorily utilised and reasonable results obtained.

7.4 Plough Draught

This analysis consists of two mains parts, first, analysis of data supplied by D. Gee-Clough at the N.I.A.E., second, analysis of data obtained from the field experiment conducted at Bush (section 5.1).

7.4.1 Preliminary Analysis

This analysis was carried out in order to calculate values of the coefficients K_5 and K_6 in the equation 4.17 and reconfirm values of coefficients K_3 and K_4 in equation 4.15.

The data used in this analysis were obtained for fields with three different soil types, namely, clay loam, sandy clay loam and sandy loam with three different types of surface cover, stubble, grass and bare soil (after the potato crop). Regression analyses were carried out for each soil individually and for all soils together using π (PI) terms suggested by Gee-Clough et al (1978) and terms involving cone index and plough lateral directional angles.

When all the data were used together in the analysis, a higher correlation coefficient of 0.98 was obtained for the N.I.A.E. equation while a lower coefficient of 0.96 was obtained for the equation proposed by the author. Similar results were obtained for sandy clay loam with stubble surface cover and the correlation coefficient dropped from 0.99 for the N.I.A.E. equation to 0.96 for the E.S.C.A. equation.

For clay loamy soil on stubble land and sandy loam soil on grass land no variation was noticed on the correlation coefficients for both equations but for clay loamy soil on potato land, a slightly higher coefficient of 1.00 was obtained for the E.S.C.A. equation as opposed to the 0.99 for the N.I.A.E. equation. Results of this analysis are given in Table 7.18.

TABLE 7.18: Regression and correlation coefficients and standard errors on regression coefficients for the two types of equations for different soil types and surface covers individually and together.

REFERENCE	SOIL TYPE	SURFACE COVER	THE NIAE EQUATION				CORRELATION COEFFICIENT	THE ESCA EQUATION (EQU. INCOPORATING CONE INDEX)				CORRELATION COEFFICIENT
			COEFFICIENTS		STANDARD ERROR			COEFFICIENTS		STANDARD ERROR		
			K_3	K_4	K_3	K_4		K_5	K_6	K_5	K_6	
1	CLAY LOAM	STUBBLE	14.36	2.85	0.5482	0.3876	0.99	0.0649	8.294	0.0025	1.081	0.99
2	SANDY LOAM	GRASS	12.06	2.16	0.5858	0.4337	1.00	0.0343	5.7256	0.018	1.313	1.00
3	SANDY CLAY LOAM	STUBBLE	11.48	1.98	0.6690	0.4560	0.99	0.0434	8.3816	0.0054	2.2906	0.96
4	CLAY LOAM	AFTER POTATO	15.32	4.34	1.3384	1.1090	0.99	0.0622	12.2645	0.0051	2.8556	1.00
5	ALL SOILS	GENERAL	13.34	2.40	0.4961	0.3498	0.98	0.0493	9.6781	0.0028	1.3271	0.96

For each soil, the Tables 7.19 - 7.22 show the soil moisture content, cone index, specific weight, ploughing speed, depth of cut and plough draught measured and predicted by the specific and general equations of both the N.I.A.E. (4.16) and E.S.C.A. (4.18) types using coefficients given in Table 7.18.

For a clay loam soil on stubble land, a very good prediction was obtained using the equations specific to that soil in both cases, i.e. using N.I.A.E. and E.S.C.A. equations. Only 3 data points were predicted beyond ±25% of accuracy (figures 7.18 and 7.19). This accuracy decreased considerably when general equations were used in both cases and 11 and 19 data points were predicted beyond ±25% using N.I.A.E. and E.S.C.A. equations, respectively (figures 7.20 and 7.21).

For clay loam soil after the potato crop, the very good prediction (all points within ±25%) was obtained using specific equations in both cases (figures 7.22 and 7.23). This accuracy was slightly decreased when the E.S.C.A. general equation was used and further deteriorated when the N.I.A.E. general equation was utilised for calculations, i.e. two and three data points were beyond the -25% boundary for the E.S.C.A. and N.I.A.E. equations, respectively (figures 7.20 and 7.21).

An average of 40% over-prediction resulted when the E.S.C.A. general equation was employed for the calculation of plough draught (figure 7.24) and the best prediction was obtained using the E.S.C.A. specific equation for sandy loam soil on grass land (figure 7.25), which predicted all the data in the range of ±25%. The remaining two equations (N.I.A.E. specific and general) also gave a good prediction of the results (figures 7.20 and 7.24).

The use of general equations in both cases for sandy clay loam on stubble land while causing some loss of accuracy in prediction of plough draught (figures 7.20 and 7.21) did overcome the slight under-prediction which occurred when the E.S.C.A. type equation specific to that soil was used in calculations (figure 7.27). The best predicted results for this soil were obtained using the N.I.A.E. specific equation(Figure 7.26).

TABLE 7.19:

The NIAE field data, predicted plough draught using the NIAE and ESCA equations and their standard deviations from the measured values for a sandy loam soil on stubble land

SOIL MOISTURE CONTENT (% $^{w}/_{w}$)	CONE INDEX (kPa)	SOIL SPECIFIC WEIGHT (kN/m^3)	TRAVEL SPEED (km/h)	PLOUGHING DEPTH (m)	SPECIFIC PLOUGH DRAUGHT (kN)								
						PREDICTED							
						NIAE EQUATIONS				ESCA EQUATIONS			
					MEASURED	SPECIFIC	S.D.	GENERAL	S.D.	SPECIFIC	S.D.	GENERAL	S.D.
22.7	0648	16.3	2.32	0.222	3.32	4.26	-1.23	3.93	-0.65	3.48	-0.21	2.71	0.44
22.7	0648	16.3	2.95	0.215	3.16	4.09	-1.22	3.77	-0.82	3.47	-0.40	2.74	0.30
22.7	0648	16.3	4.81	0.219	3.36	4.65	-1.70	4.26	-0.95	3.97	-0.79	3.30	0.04
22.7	0648	16.3	4.74	0.215	3.44	4.47	-1.36	4.10	-0.70	3.88	-0.56	3.21	0.16
22.7	0648	16.3	6.00	0.212	3.98	4.73	-0.99	4.31	-0.35	4.22	-0.31	3.63	0.25
22.7	0648	16.3	5.61	0.203	3.50	4.26	1.00	3.88	-0.40	3.91	-0.53	3.33	0.12
22.7	0648	16.3	6.24	0.198	4.50	4.26	0.30	3.87	0.65	4.02	0.61	3.48	0.75
22.7	0648	16.3	8.51	0.222	5.10	6.19	-1.44	5.57	-0.50	5.53	-0.55	5.09	0.00
22.7	0648	16.3	8.84	0.215	5.04	6.03	-1.31	5.41	-0.40	5.52	-0.62	5.13	-0.07
29.7	0650	14.1	2.20	0.224	3.92	3.73	0.24	3.45	0.49	3.49	0.54	2.70	0.90
29.7	0650	14.1	2.71	0.219	3.76	3.63	0.16	3.35	0.42	3.48	0.35	2.71	0.77
29.7	0650	14.1	4.35	0.207	4.10	3.52	0.75	3.23	0.91	3.57	0.67	2.90	0.88
29.7	0650	14.1	4.69	0.220	4.44	4.03	0.53	3.69	0.78	3.87	0.72	3.17	0.93
29.7	0650	14.1	4.96	0.231	5.20	4.48	0.94	4.10	1.15	4.14	1.35	3.42	1.31
29.7	0650	14.1	4.33	0.217	4.54	3.85	0.90	3.53	1.06	3.74	1.02	3.03	1.11
29.7	0650	14.1	5.35	0.227	5.56	4.44	1.46	4.06	1.58	4.18	1.77	3.48	1.53
29.7	0650	14.1	6.85	0.215	6.90	4.46	3.20	4.04	3.01	4.42	3.17	3.84	2.26
29.7	0650	14.1	6.76	0.220	7.24	4.61	3.45	4.19	3.22	4.49	3.52	3.90	2.47
35.2	0651	14.5	2.15	0.238	4.08	4.32	-0.32	4.00	0.08	3.71	0.46	2.87	0.89
35.2	0651	14.5	2.65	0.238	4.28	4.39	-0.14	4.05	0.23	3.78	0.63	2.95	0.98
35.2	0651	14.5	4.15	0.235	4.48	4.55	-0.10	4.19	0.30	4.02	0.57	3.26	0.90
35.2	0651	14.5	4.90	0.230	4.64	4.55	0.10	4.17	0.49	4.13	0.65	3.41	0.90
35.2	0651	14.5	5.60	0.227	4.70	4.64	0.07	4.32	0.48	4.28	0.53	3.60	0.81
35.2	0651	14.5	6.80	0.240	5.30	5.55	-0.33	5.04	0.27	4.96	0.43	0.72	0.72
35.2	0651	14.5	6.26	0.234	5.42	5.11	0.39	4.66	0.80	4.64	1.00	3.97	1.06
35.2	0651	14.5	8.56	0.232	5.60	5.95	-0.46	5.36	0.25	5.56	0.04	5.07	0.39
35.2	0651	14.5	8.70	0.226	6.24	5.76	0.62	5.18	1.11	5.48	0.96	5.01	0.90
23.8	0809	15.6	2.10	0.237	4.92	4.60	0.41	4.26	0.69	4.56	0.45	3.52	1.03
23.8	0809	15.6	2.39	0.235	5.30	4.56	0.96	4.22	1.13	4.56	0.93	3.54	1.30
23.8	0809	15.6	3.80	0.236	5.14	4.86	0.36	4.47	0.70	4.85	0.36	3.87	0.94
23.8	0809	15.6	4.88	0.234	5.40	5.05	0.45	4.63	0.80	5.10	0.37	4.17	0.90
23.8	0809	15.6	5.78	0.234	4.86	5.33	-0.62	4.87	-0.01	5.40	-0.69	4.51	0.25
23.8	0809	15.6	7.09	0.225	4.84	5.44	-0.79	4.93	-0.09	5.69	-1.09	4.92	-0.06
23.8	0809	15.6	5.52	0.229	5.32	5.04	0.35	4.61	0.74	5.19	0.15	4.31	0.74
23.8	0809	15.6	8.49	0.239	6.20	6.69	-0.65	6.03	0.17	6.73	-0.68	6.03	0.12
23.8	0809	15.6	8.57	0.239	6.24	6.73	-0.65	6.07	0.17	6.77	-0.68	6.08	0.11
28.3	0987	14.7	2.11	0.234	5.06	4.23	1.08	3.91	1.20	5.46	-0.52	4.20	0.63
28.3	0987	14.7	2.59	0.232	4.78	4.22	0.73	3.90	0.92	5.48	-0.90	4.24	0.39
28.3	0987	14.7	4.26	0.233	4.92	4.57	0.45	4.20	0.75	5.83	-1.18	4.64	0.20
28.3	0987	14.7	4.90	0.235	5.30	4.80	0.64	4.40	0.94	6.05	-0.97	4.88	0.30
28.3	0987	14.7	5.61	0.226	5.10	4.67	0.56	4.26	0.88	6.03	-1.20	4.94	0.11
28.3	0987	14.7	6.38	0.220	5.90	4.68	1.59	4.26	1.73	6.10	-0.29	5.10	0.59
28.3	0987	14.7	8.23	0.218	4.80	5.30	-0.66	4.77	0.02	6.80	-2.57	5.90	-0.82
28.3	0987	14.7	8.91	0.217	5.90	5.55	0.45	4.98	0.96	7.08	-1.51	6.24	-0.25
28.3	0987	14.7	7.83	0.223	6.44	5.33	1.44	4.82	1.71	6.77	-0.43	5.83	0.44
22.8	0669	15.7	2.30	0.236	4.02	4.62	-0.79	4.27	-0.27	3.81	0.26	2.96	0.78
22.8	0669	15.7	2.94	0.238	3.92	4.80	-1.16	4.43	-0.54	3.95	-0.04	3.11	0.60
22.8	0669	15.7	3.55	0.234	4.24	4.76	-0.68	4.38	-0.15	4.00	0.29	3.20	0.77
22.8	0669	15.7	4.98	0.232	4.96	4.99	-0.05	4.61	0.36	4.32	0.81	3.59	1.01
22.8	0669	15.7	5.18	0.230	4.94	5.01	-1.10	4.59	0.37	4.37	0.73	3.65	0.95
22.8	0669	15.7	6.77	0.226	5.62	5.39	0.29	4.89	0.76	4.86	0.97	4.25	1.01
22.8	0669	15.7	6.86	0.222	5.46	5.26	0.26	4.77	0.72	4.81	0.83	4.21	0.92
22.8	0669	15.7	8.36	0.232	6.34	6.34	-1.01	5.72	0.65	5.73	0.78	5.22	0.82
22.8	0669	15.7	8.27	0.224	6.14	5.94	0.25	5.35	0.82	5.48	0.83	4.99	0.85
25 2	0772	14.8	2.38	0.234	3.84	4.29	-0.60	3.97	-0.14	4.06	-0.29	3.15	0.50
25.2	0772	14.8	2.90	0.236	3.62	4.44	-1.08	4.10	-0.51	4.18	-0.72	3.27	0.25
25.2	0772	14.8	4.47	0.233	4.40	4.65	-0.33	4.27	0.13	4.46	-0.08	3.62	0.57
25.2	0772	14.8	5.03	0.236	4.48	4.91	-0.57	4.50	-0.02	4.68	-0.26	3.85	0.46
25.2	0772	14.8	5.97	0.239	4.60	5.32	-0.95	4.85	-0.27	5.04	-0.57	4.26	0.24
25.2	0772	14.8	7.04	0.228	4.62	5.26	-0.85	4.77	-0.16	5.21	-0.76	4.53	0.06
25.2	0772	14.8	6.85	0.231	4.84	5.31	-0.62	4.82	0.01	5.20	-0.46	4.50	0.25
25.2	0772	14.8	8.59	0.226	5.04	5.83	-1.04	5.24	-0.21	5.84	-1.04	5.28	-0.18
25.2	0772	14.8	9.37	0.226	5.54	6.20	-0.87	5.56	-0.02	6.24	-0.90	5.74	-0.15
26.9	0813	15.5	2.16	0.221	3.36	3.99	-0.83	3.69	-0.35	4.28	-1.19	3.30	0.03
26.9	0813	15.5	2.43	0.220	3.70	3.99	-0.38	3.69	0.00	4.30	-0.77	3.33	0.27
26.9	0813	15.5	2.50	0.226	4.84	4.21	0.81	3.90	0.99	4.43	0.52	3.43	1.03
26.9	0813	15.5	4.35	0.231	4.44	4.76	-0.43	4.37	0.06	4.91	-0.60	3.96	0.35
26.9	0813	15.5	4.13	0.230	5.22	4.67	0.71	4.29	0.97	4.83	0.49	3.87	0.99
26.9	0813	15.5	6.75	0.231	5.56	5.52	0.04	5.02	0.57	5.71	-0.19	4.89	0.49
26.9	0813	15.5	7.09	0.226	5.22	5.45	-0.30	4.94	0.29	5.72	-0.65	4.95	0.19
26.9	0813	15.5	7.74	0.228	7.34	5.80	2.01	5.24	2.21	6.06	1.63	5.33	1.48
26.9	0813	15.5	7.07	0.235	6.90	5.82	1.41	5.28	1.70	5.94	1.22	5.14	1.30

TABLE 7.20: The NIAE field data, predicted plough draught using the NIAE and ESCA equations and their standard deviations from the measured values for a sandy clay loam soil on stubble land

REFERENCE	SOIL MOISTURE CONTENT (% $^{w}/w$)	CONE INDEX (kPa)	SOIL SPECIFIC WEIGHT (kN/m^3)	TRAVEL SPEED (km/h)	PLOUGHING DEPTH (m)	SPECIFIC PLOUGH DRAUGHT (kN)									
						MEASURED	PREDICTED								
							NIAE EQUATIONS				ESCA EQUATIONS				
							SPECIFIC	S.D.	GENERAL	S.D.	SPECIFIC	S.D.	GENERAL	S.D.
1	21.5	0905	16.6	2.34	0.202	3.18	2.86	0.42	3.33	-0.16	2.98	0.14	3.38	-0.15
2	21.5	0905	16.6	2.88	0.209	3.32	3.12	0.27	3.63	-0.32	3.16	0.11	3.60	-0.20
3	21.5	0905	16.6	4.68	0.217	3.94	3.63	0.42	4.23	-0.31	3.70	0.17	4.22	-0.20
4	21.5	0905	16.6	4.85	0.225	4.34	3.91	0.57	4.57	-0.25	3.89	0.33	4.43	-0.07
5	21.5	0905	16.6	4.09	0.222	4.14	3.68	0.62	4.29	-0.16	3.62	0.38	4.12	0.00
6	21.5	0905	16.6	5.69	0.222	4.52	4.00	0.70	4.68	-0.17	4.11	0.30	4.69	-0.13
7	21.5	0905	16.6	6.77	0.232	4.80	4.62	0.23	5.42	-0.66	4.73	0.04	5.41	-0.45
8	21.5	0905	16.6	6.82	0.231	5.00	4.60	0.53	5.40	-0.42	4.74	0.19	5.41	-0.31
9	21.5	0905	16.6	8.42	0.230	5.34	5.08	0.34	5.98	-0.68	5.50	-0.12	6.31	-0.71
10	21.5	0905	16.6	8.90	0.230	5.54	5.26	0.37	6.20	-0.70	5.77	-0.17	6.62	-0.80
11	15.8	1143	17.4	2.12	0.246	3.86	4.40	-0.74	5.12	-1.33	4.50	-0.48	5.12	-0.93
12	15.8	1143	17.4	2.77	0.242	3.52	4.34	-1.11	5.04	-1.61	4.54	-0.76	5.16	-1.22
13	15.8	1143	17.4	4.65	0.243	3.82	4.70	-1.20	5.48	-1.76	5.06	-0.92	5.77	-1.44
14	15.8	1143	17.4	5.03	0.241	3.98	4.71	-1.00	5.50	-1.61	5.15	-0.87	5.87	-1.40
15	15.8	1143	17.4	6.81	0.241	3.92	5.20	-1.75	6.10	-2.30	5.90	-1.47	6.74	-2.09
16	15.8	1143	17.4	7.27	0.242	3.90	5.39	-2.03	6.33	-2.57	6.15	-1.67	7.03	-2.32
17	15.8	1143	17.4	7.85	0.241	4.84	5.56	-0.98	6.53	-1.79	6.44	-1.19	7.37	-1.87
18	15.8	1143	17.4	8.37	0.241	4.24	5.75	-2.06	6.77	-2.67	6.74	-1.85	7.71	-2.57
19	15.8	1143	17.4	9.72	0.247	6.00	6.58	-0.79	7.76	-1.87	7.99	-1.47	9.15	-2.34
20	19.1	0602	15.7	2.39	0.245	3.40	3.97	-0.77	4.61	-1.28	2.46	0.69	2.80	0.44
21	19.1	0602	15.7	2.81	0.243	3.52	3.95	-0.59	4.59	-1.14	2.51	0.74	2.86	0.48
22	19.1	0602	15.7	4.05	0.247	4.32	4.26	0.07	4.96	-0.68	2.83	1.10	3.23	0.80
23	19.1	0602	15.7	5.05	0.243	4.32	4.32	-0.00	5.05	-0.77	3.08	0.91	3.52	0.59
24	19.1	0602	15.7	5.79	0.248	4.66	4.66	-0.01	5.45	-0.84	3.41	0.92	3.90	0.56
25	19.1	0602	15.7	6.07	0.245	5.70	4.73	1.30	5.42	0.29	3.52	1.61	4.02	1.23
26	19.1	0602	15.7	5.45	0.243	5.60	4.41	1.61	5.15	0.46	3.22	1.76	3.67	1.42
27	19.1	0602	15.7	7.98	0.248	7.10	5.31	2.42	6.24	0.90	4.40	1.99	5.05	1.51
28	19.1	0602	15.7	8.55	0.245	6.00	5.40	0.80	6.36	-0.38	4.66	0.99	5.35	0.48
29	18.2	0729	16.3	1.95	0.288	4.16	3.47	0.92	4.11	0.05	2.66	1.10	3.02	0.83
30	18.2	0729	16.3	2.31	0.226	4.12	3.50	0.83	4.07	0.04	2.71	1.04	3.08	0.76
31	18.2	0729	16.3	4.07	0.234	4.08	3.99	0.11	4.65	-0.61	3.17	0.67	3.61	0.34
32	18.2	0729	16.3	4.87	0.233	4.04	4.11	-0.10	4.80	-0.80	3.38	0.48	3.86	0.13
33	18.2	0729	16.3	5.92	0.238	4.26	4.52	-0.36	5.29	-1.09	3.83	0.31	4.37	-0.08
34	18.2	0729	16.3	6.81	0.237	5.04	4.73	0.41	5.54	-0.53	4.18	0.63	4.79	0.18
35	18.2	0729	16.3	5.85	0.239	5.20	4.54	0.89	5.31	-0.12	3.82	1.02	4.36	0.61
36	18.2	0729	16.3	8.32	0.238	5.84	5.26	0.78	6.18	-0.36	4.95	0.65	5.68	0.11
37	18.2	0729	16.3	7.59	0.238	5.44	5.01	0.58	5.88	-0.46	4.57	0.64	5.23	0.14

TABLE 7.21: The NIAE field data, predicted plough draught using the NIAE and ESCA equations and their standard deviation, from the measured values for a clay loam soil after potato crop.

REFERENCE	SOIL MOISTURE CONTENT (% $^{w}/w$)	CONE INDEX (kPa)	SOIL SPECIFIC WEIGHT (kNm^{3})	TRAVEL SPEED (km/h)	PLOUGHING DEPTH (m)	SPECIFIC PLOUGH DRAUGHT (kN/FURROW)								
						MEASURED	PREDICTED							
							NIAE EQUATIONS				ESCA EQUATIONS			
							SPECIFIC	S.D.	GENERAL	S.D.	SPECIFIC	S.D.	GENERAL	S.D.
1	23.6	0777	14.1	2.30	0.222	3.52	3.98	-0.82	3.40	0.12	4.02	-0.94	3.18	0.246
2	23.6	0777	14.1	2.37	0.288	3.92	3.92	-0.52	3.59	0.34	4.14	-0.42	3.28	0.470
3	23.6	0777	14.1	4.08	0.227	4.18	4.60	-0.75	3.80	0.39	4.56	-0.72	3.61	0.417
4	23.6	0777	14.1	4.61	0.225	4.84	4.70	0.23	3.83	1.05	4.70	0.24	3.72	0.823
5	23.6	0777	14.1	5.35	0.219	4.88	4.75	0.21	3.80	1.14	4.86	0.02	3.85	0.761
6	23.6	0777	14.1	6.23	0.218	5.64	5.10	0.95	3.98	1.75	5.23	0.76	4.14	1.109
7	23.6	0777	14.1	5.00	0.224	5.72	4.81	1.59	3.88	1.93	4.83	1.65	3.82	1.401
8	23.6	0777	14.1	8.30	0.231	6.10	6.82	-1.28	5.07	1.07	6.76	-1.24	5.35	0.553
9	23.6	0777	14.1	6.71	0.230	6.14	5.83	0.53	4.52	1.71	5.77	0.68	4.56	1.164

TABLE 7.22: The NIAE field data, predicted plough draught using the NIAE and ESCA equations and their standard deviations from the measured values for sandy loam soil on grass land.

REFERENCE	SOIL MOISTURE CONTENT (% $^{w}/w$)	CONE INDEX (kPa)	SOIL SPECIFIC WEIGHT (kN/m^3)	TRAVEL SPEED (km/h)	PLOUGHING DEPTH (m)	SPECIFIC PLOUGH DRAUGHT (kN)									
							PREDICTED								
							NIAE EQUATIONS				ESCA EQUATIONS				
						MEASURED	SPECIFIC	S.D.	GENERAL	S.D.	SPECIFIC	S.D.	GENERAL	S.D.
1	27.4	1357	15.9	2.19	0.242	4.08	4.10	-0.08	4.53	-0.48	4.11	-0.11	5.94	-1.37
2	27.4	1357	15.9	2.27	0.244	4.52	4.18	1.03	4.62	-0.10	4.16	1.02	6.00	-1.10
3	27.4	1357	15.9	4.23	0.244	4.34	4.48	-0.44	4.95	-0.65	4.44	-0.44	6.49	-1.59
4	27.4	1357	15.9	4.74	0.241	4.30	4.48	-0.57	4.95	-0.69	4.49	-0.35	6.58	-1.69
5	27.4	1357	15.9	5.50	0.241	4.72	4.66	0.16	5.15	-0.46	4.66	0.14	6.87	-1.59
6	27.4	1357	15.9	6.84	0.238	4.52	4.93	-1.29	5.46	-0.97	4.97	0.13	7.40	-2.13
7	27.4	1357	15.9	7.01	0.239	5.00	5.03	-0.09	5.56	-0.59	5.04	0.66	7.52	-2.23
8	27.4	1357	15.9	8.40	0.237	5.24	5.44	-0.63	6.02	-0.83	5.47	0.55	8.25	-2.23
9	27.4	1357	15.9	8.06	0.243	6.14	5.55	1.81	6.14	-0.00	5.48	1.84	8.25	-1.56

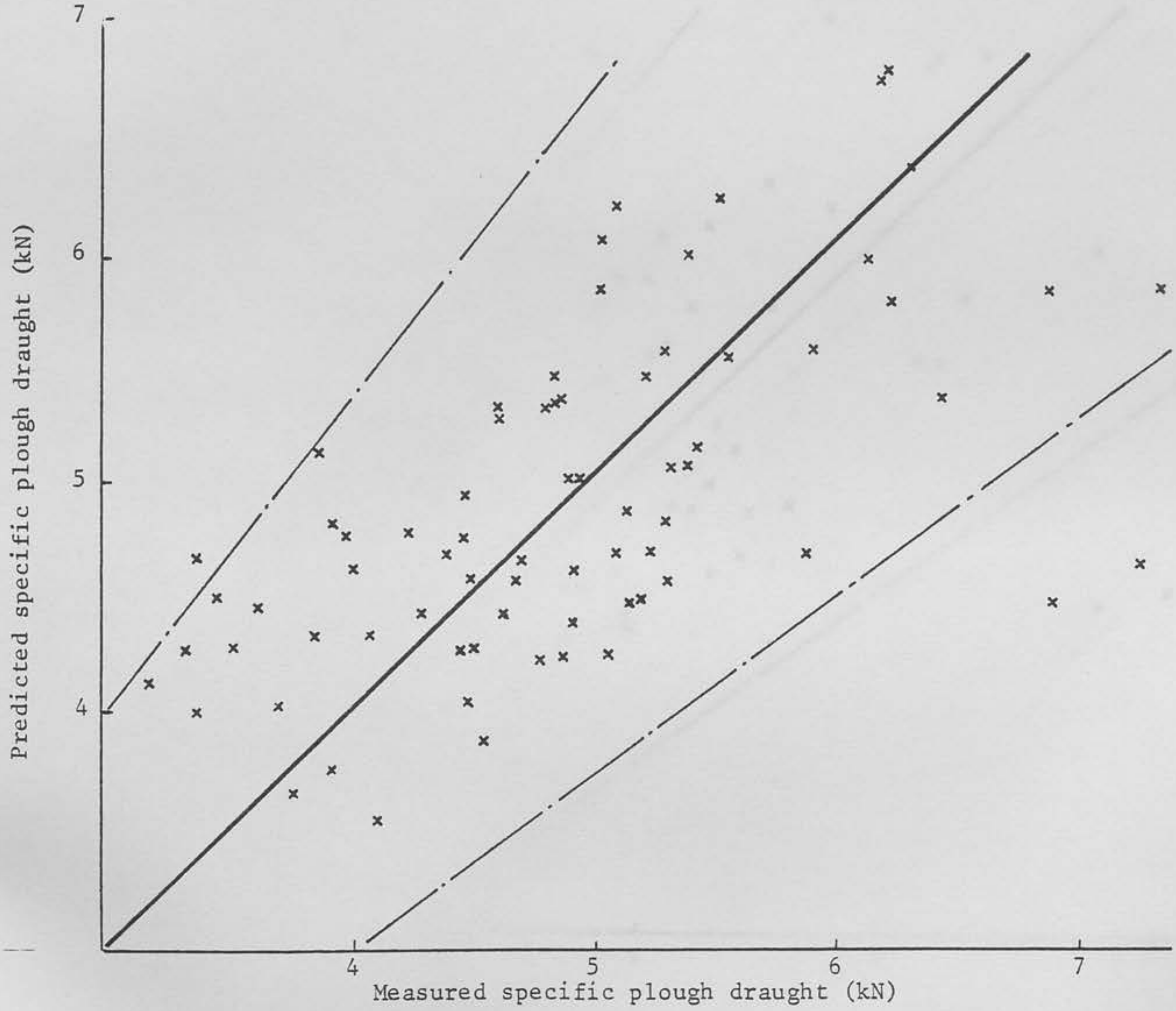

FIG. 7.18: Measured and predicted values of specific plough draught using the N.I.A.E. specific equation for a clay loam soil on stubble land.

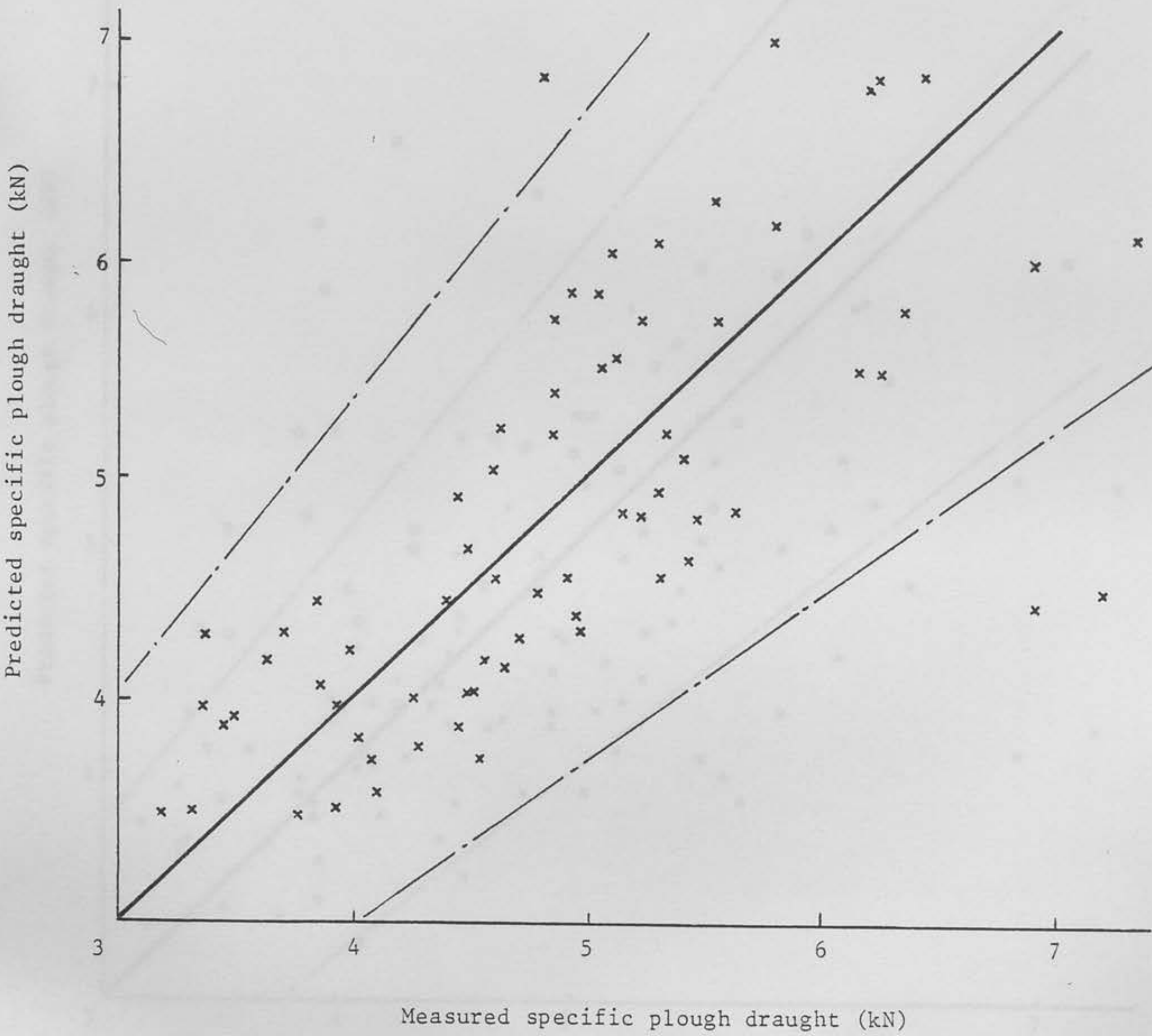

FIG. 7.19: Measured and predicted values of the specific plough draught, using the ESCA specific equation for a clay loam soil on stubble land.

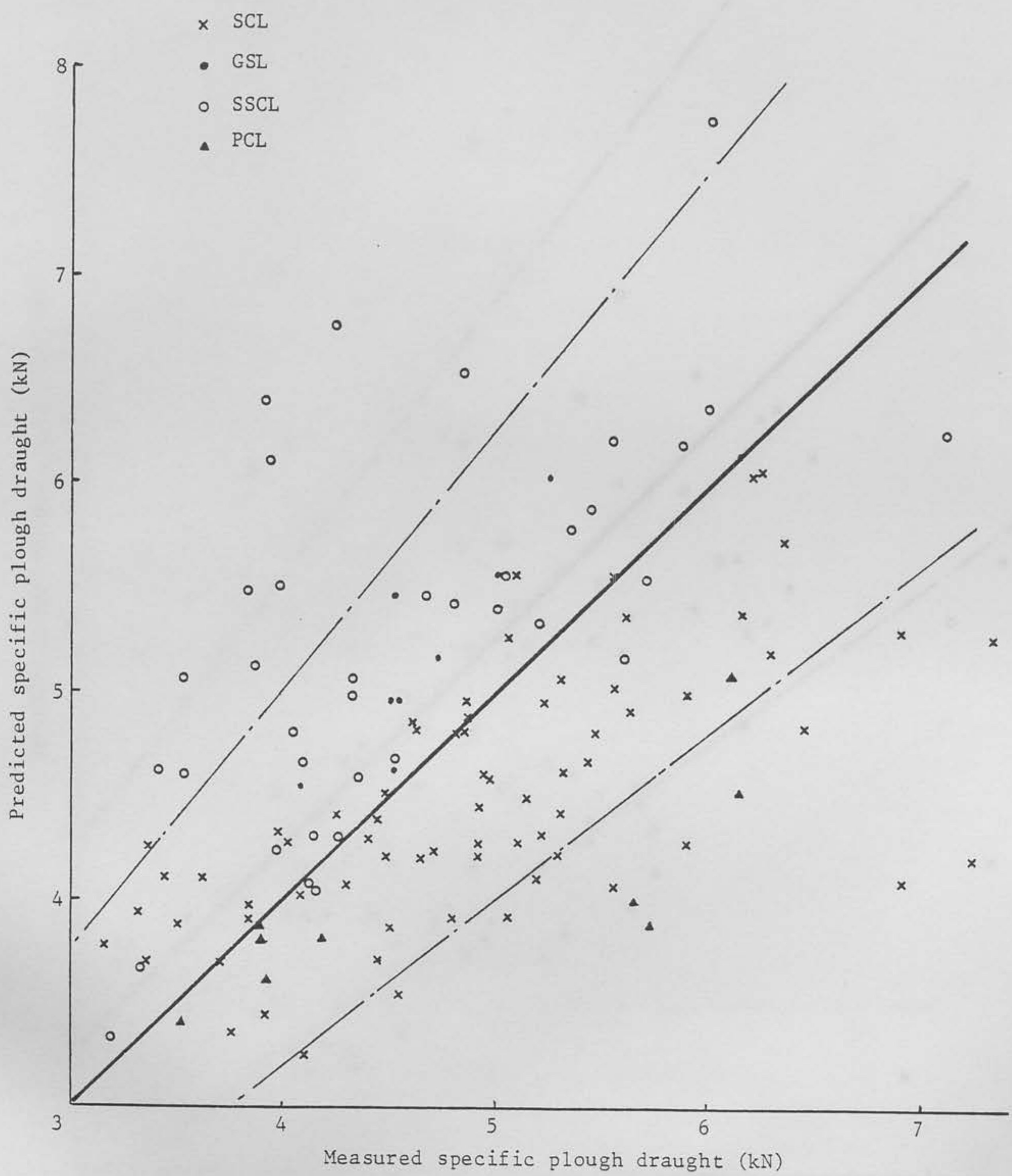

FIG. 7.20: Measured and predicted plough draught using the NIAE general equation for all soils.

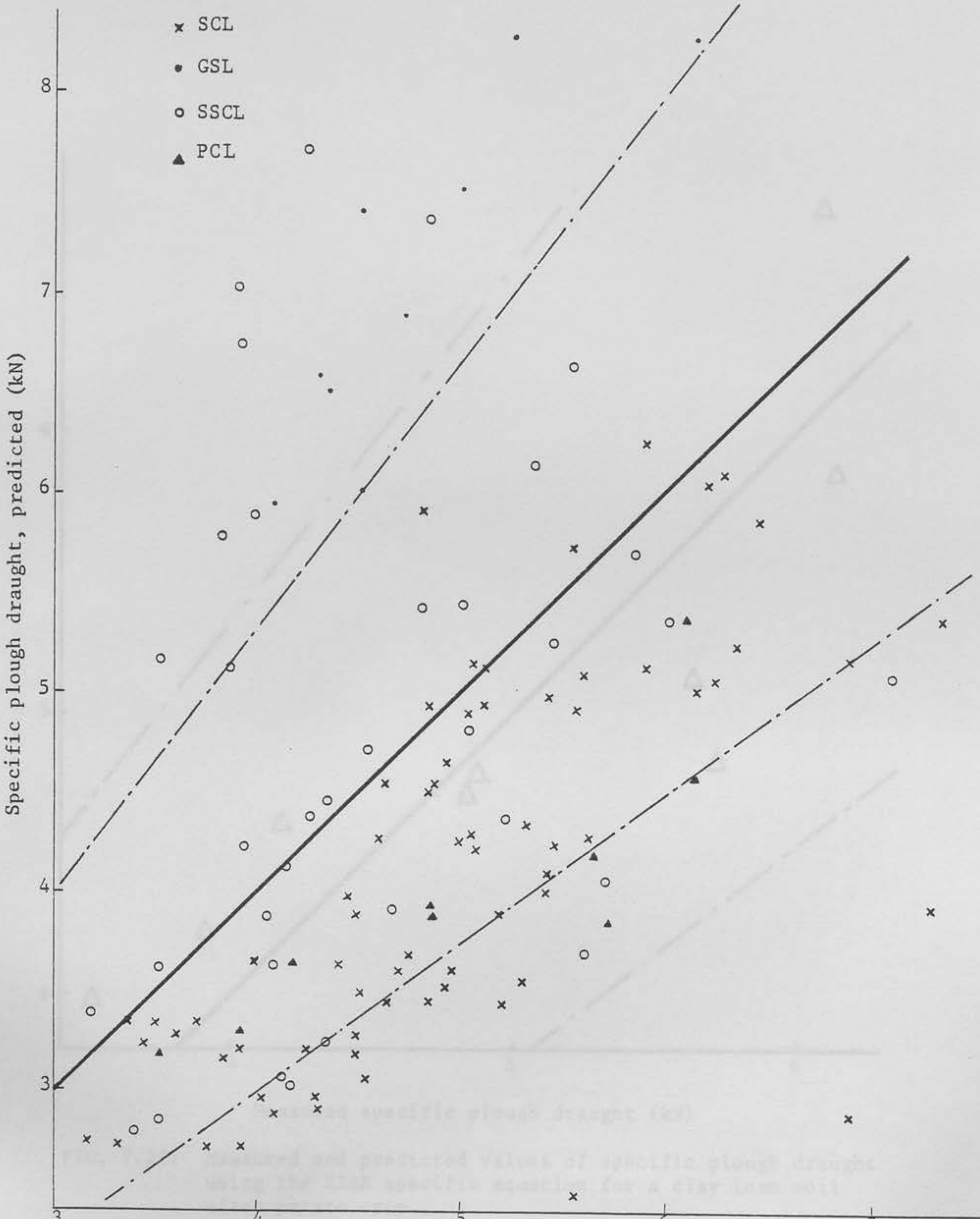

FIG. 7.21: Measured and predicted values of plough draught using the E.S.C.A general equation.

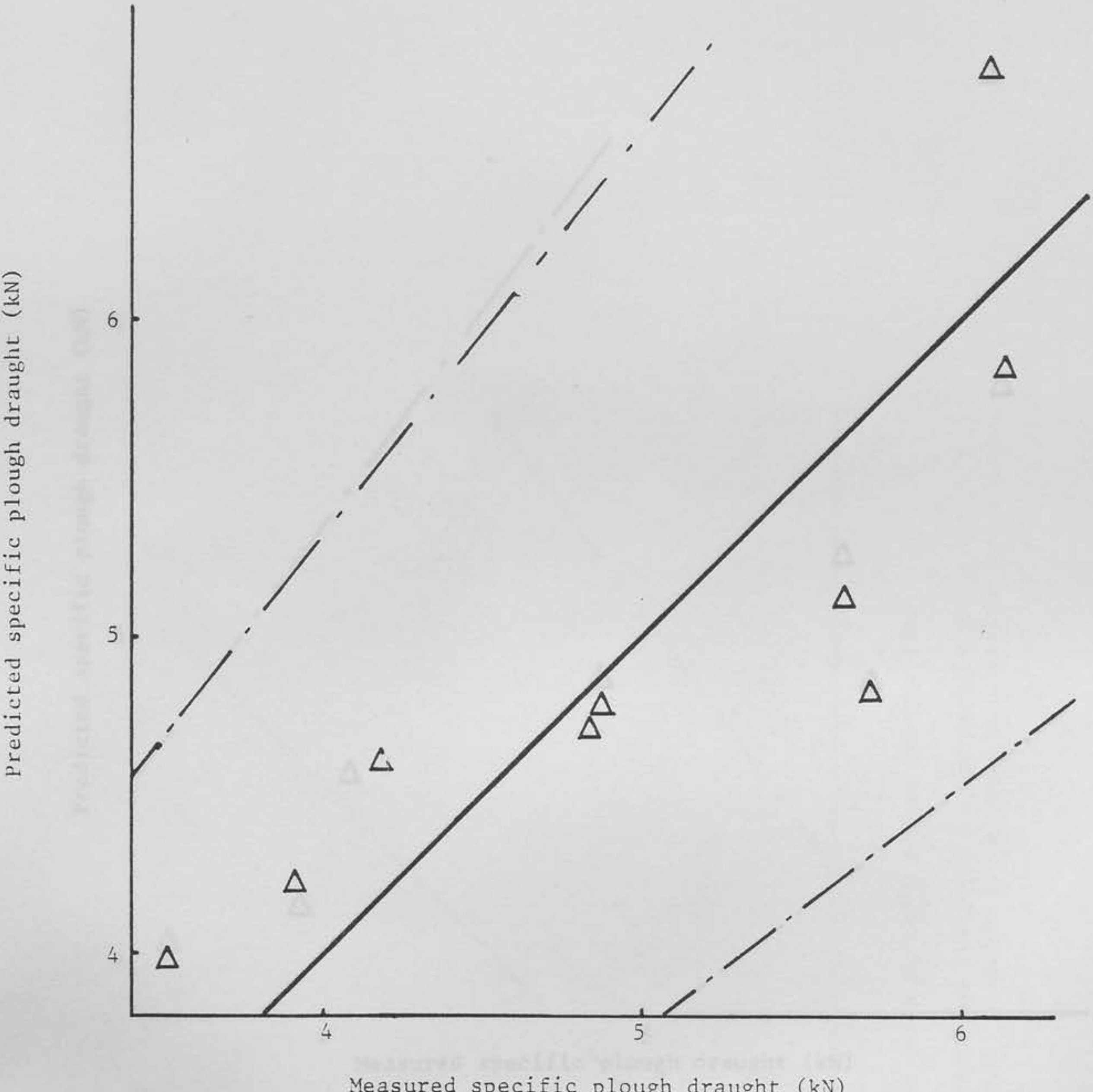

FIG. 7.22: Measured and predicted values of specific plough draught using the NIAE specific equation for a clay loam soil after potato crop.

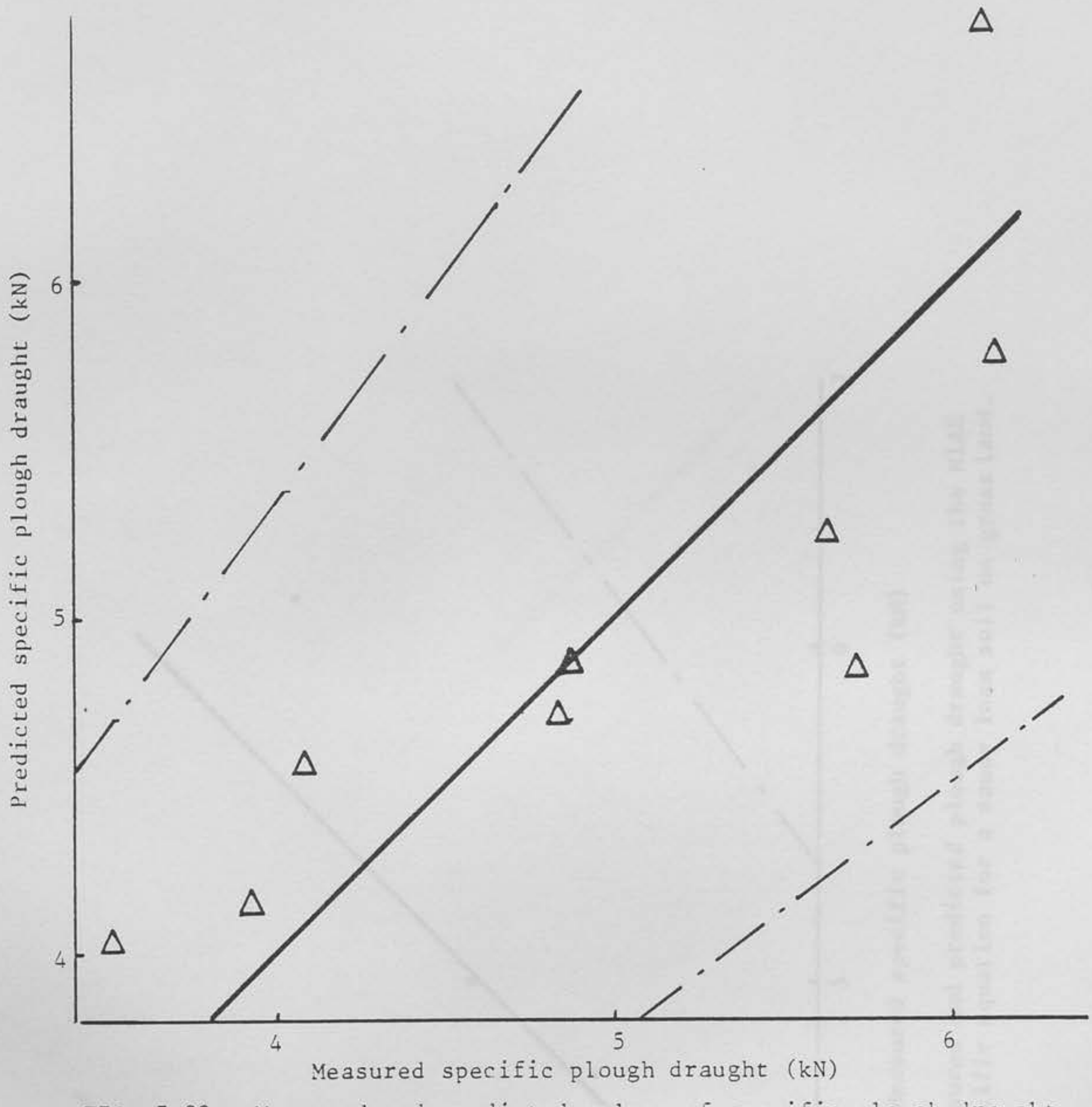

FIG. 7.23: Measured and predicted values of specific plough draught using the E.S.C.A. specific equation for a clay loam soil after potato crop.

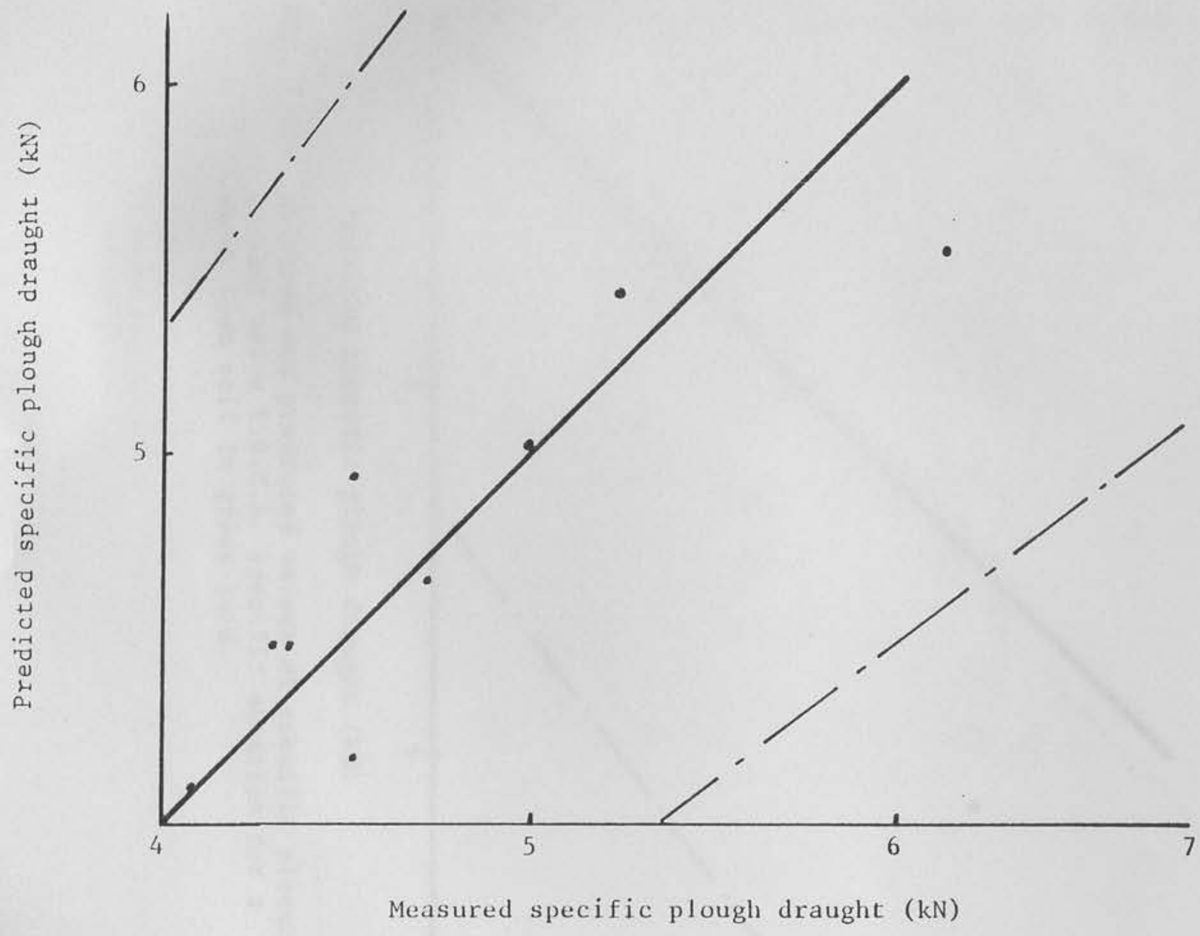

FIG. 7.24: Measured and predicted plough draught using the NIAE specific equation for a sandy loam soil on grass land.

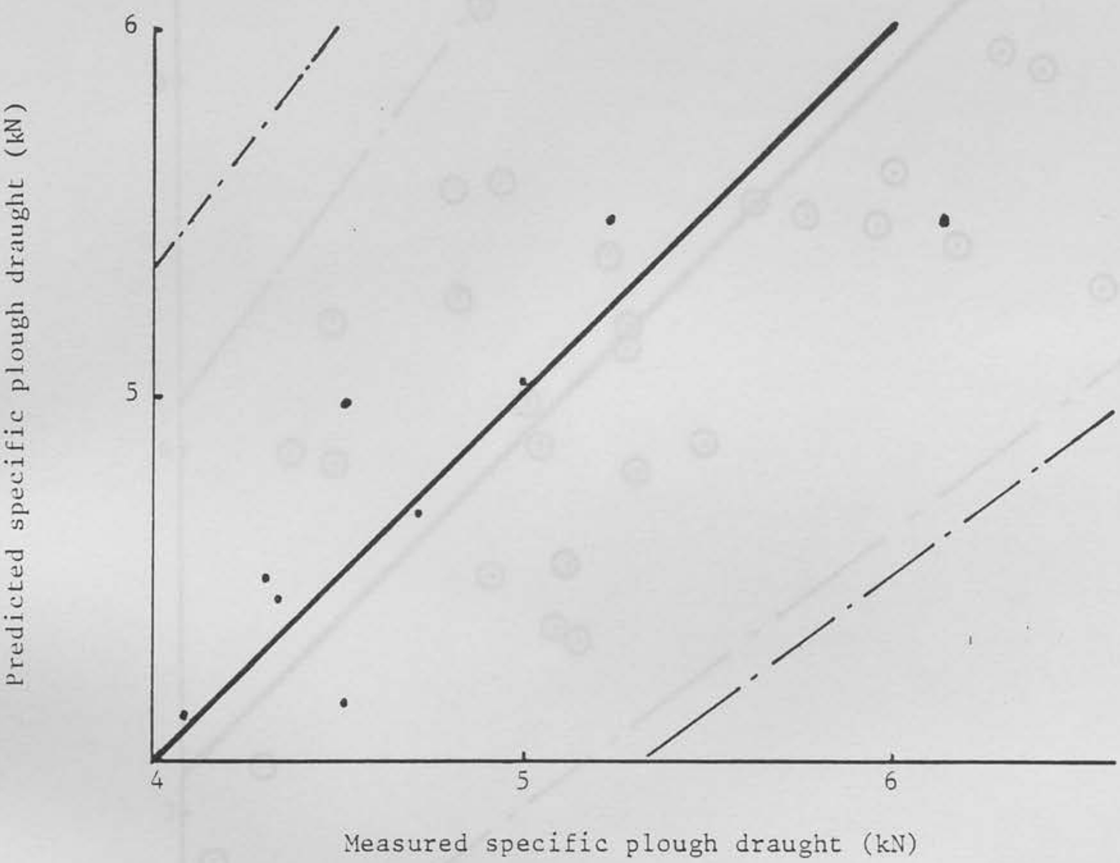

FIG. 7.25: Measured and predicted values of specific plough draught using E.S.C.A. specific equation for a sandy loam soil in grass land.

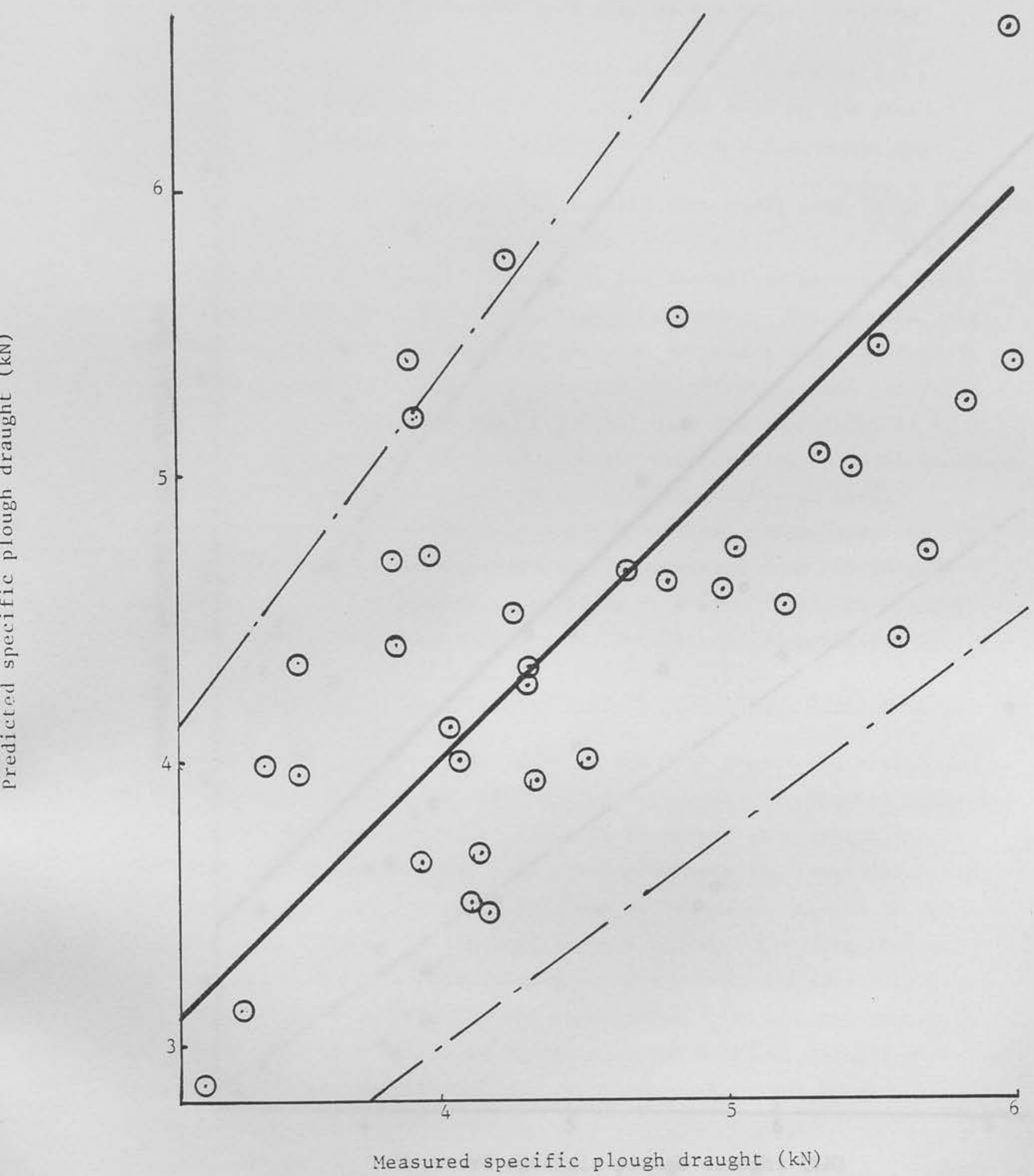

FIG. 7.26. Measured and predicted plough draught using the NIAE specific equation derived for sandy clay loam soil at stubble land.

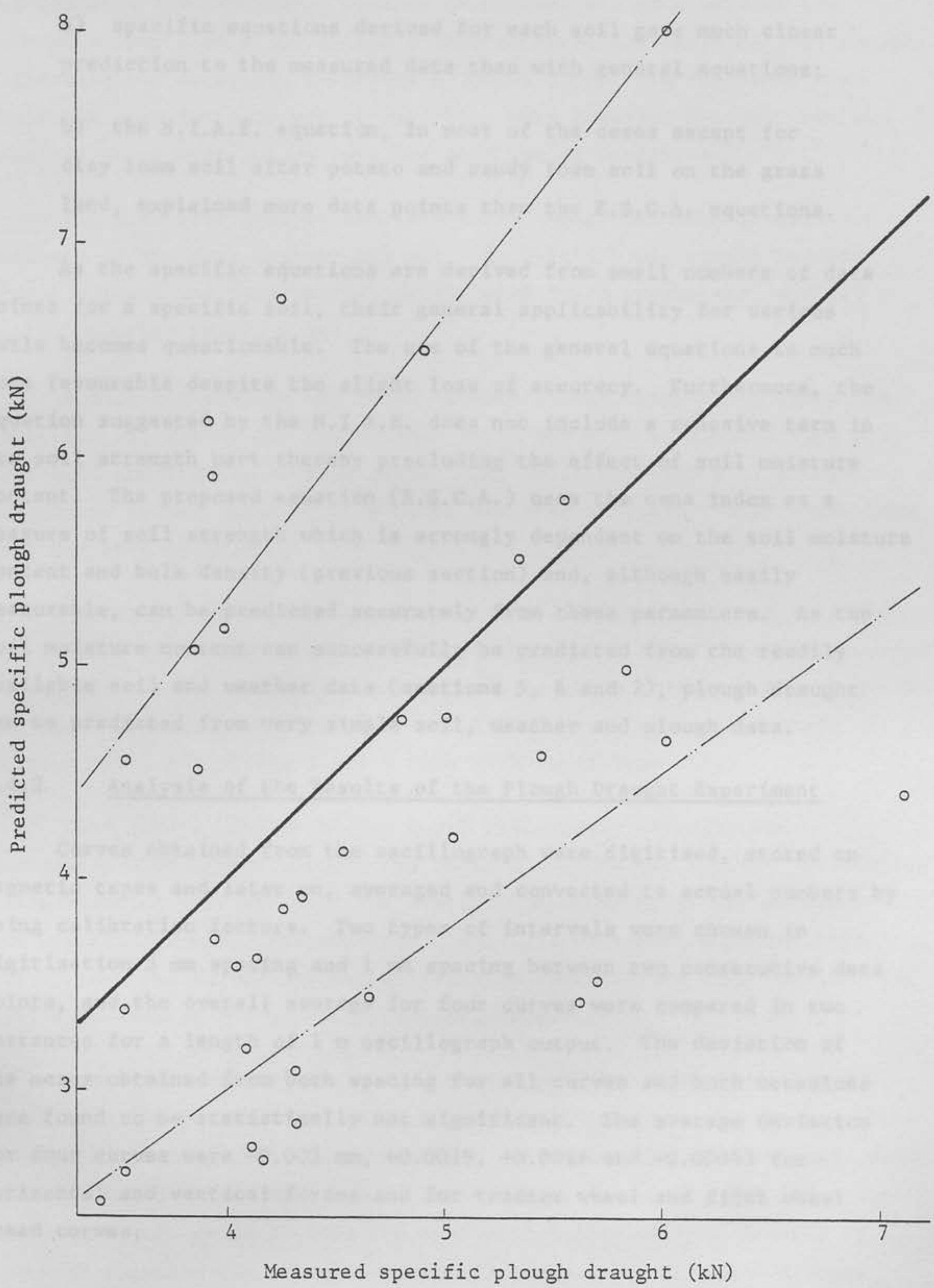

FIG. 7.27: Measured and predicted specific plough draught using E.S.C.A. specific equation for sandy clay loam soil with stubble surface cover.

From the above discussion it can be concluded that:

a) specific equations derived for each soil gave much closer prediction to the measured data than with general equations;

b) the N.I.A.E. equation, in most of the cases except for clay loam soil after potato and sandy loam soil on the grass land, explained more data points than the E.S.C.A. equations.

As the specific equations are derived from small numbers of data points for a specific soil, their general applicability for various soils becomes questionable. The use of the general equations is much more favourable despite the slight loss of accuracy. Furthermore, the equation suggested by the N.I.A.E. does not include a cohesive term in its soil strength part thereby precluding the effect of soil moisture content. The proposed equation (E.S.C.A.) uses the cone index as a measure of soil strength which is strongly dependent on the soil moisture content and bulk density (previous section) and, although easily measurable, can be predicted accurately from these parameters. As the soil moisture content can successfully be predicted from the readily available soil and weather data (sections 5, 6 and 7), plough draught can be predicted from very simple soil, weather and plough data.

7.4.2 Analysis of the Results of the Plough Draught Experiment

Curves obtained from the oscillograph were digitised, stored on magnetic tapes and later on, averaged and converted to actual numbers by using calibration factors. Two types of intervals were chosen in digitisation. 5 mm spacing and 1 mm spacing between two consecutive data points, and the overall average for four curves were compared in two instances for a length of 1 m oscillograph output. The deviation of the means obtained from both spacing for all curves and both occasions were found to be statistically not significant. The average deviation for four curves were -0.003 mm, +0.0019, +0.0016 and -0.00043 for horizontal and vertical forces and for tractor wheel and fifth wheel speed curves.

As the variation was not significant, a 5 mm spacing was adopted instead of a 1 mm spacing. Another comparison was made between the average output from a 300 mm and a 1000 mm curve and again no significant difference was obtained, therefore a 300 mm output was analysed. Two replicate runs for each set of variables were analysed but only one was required to provide enough data for each set of variables.

The data were grouped for each field number and some preliminary analysis of the data was carried out. Correlation was sought between plough draught and other variables for each field separately, and all fields together (Table 7.23).

A high correlation was found between plough draught and fifth wheel speed for all fields and the maximum value was 0.94 at field 3 with clay loam soil and stubble surface cover. The least dependence of plough draught on travel speed (C.R. = 0.88) occurred at field 2 with sandy loam soil and bare surface.

For slip, the highest correlation coefficient (0.96) was obtained for field 4 with sandy loam soil and stubble cover. For this field, plough draught was most dependent on soil moisture content. Plough draught was least dependent on slip (C.R. = 0.83) and soil moisture content (C.R. = 0.93) for fields 1 and 2 both with sandy loam soils.

Cone index, both at median depth and overall average, was correlated with plough draught and field 2 yielded the highest correlation coefficient of 0.97 and 0.95 for average cone indices at median depth and overall averages, respectively. When all data were analysed together, the highest and second highest correlation coefficients were obtained for soil bulk density and moisture content, respectively.

Cone index values measured in this experiment were generally 50% lower than the cone indices taken by hand-held non-recording penetrometer at similar fields. This difference was consistent for all readings taken from the fields which were common in both experiments 5.1 and 5.2. When these data were compared with the predicted values of cone indices by means of equation 4.9, correlation coefficients of 0.94 and 0.91 were

Table 7.23: Correlation coefficients and standard errors between plough draught and other variables for each field individually and all fields together.

FIELD NAME	FIELD NO.	VARIABLE NAME													
		WHEEL SPEED		5th W. SPEED		SLIP		B.D.		M.C.		CI1		CI2	
(FNA)	(FN)	C.C.	S.E.	C.C.	S.E.	C.C.	S.E.	C.C.	S.E.	C.C.	S.E.	C.C.	S.E.	C.C.	S.E.
S7	1	0.95	0.211	0.93	0.357	0.83	0.0167			0.97	-0.0088	0.97	0.0138	0.93	0.0197
FC	2	0.92	0.264	0.88	0.437	0.94	0.0104			0.93	-0.012	0.95	0.011	0.95	0.013
LF	3	0.95	0.191	0.94	0.273	0.94	0.0118			0.97	-0.007	0.96	0.009	0.94	0.011
SH	4	0.95	0.310	0.91	0.577	0.96	0.009			0.98	-0.010	0.88	0.041	0.88	0.055
HM	5	0.93	0.275	0.92	0.403	0.90	0.017			0.96	-0.009	0.94	0.015	0.91	0.020
ALL FIELDS		0.93	0.113	0.91	0.18	0.92	0.03	0.96	0.084	0.95	-0.005	0.92	0.008	0.89	0.010

obtained between predicted and measured cone indices at median depth and overall average, respectively.

7.4.3 Second Test of Plough Draught Equations

In order to test the plough draught equation proposed by the author (equation 4.18) and the N.I.A.E. (equation 4.16), the plough draught was calculated using the experimental data obtained for each field by means of both equations and a comparison was made (Table 7.24 and figures 7.28 and 7.29).

In general an over-prediction of 87%, 96% and 1% occurred when the plough draught was calculated by means of E.S.C.A. equation from the average measured cone indices at median depth, overall average and predicted cone indices by means of equation 4.9.

Correlation coefficients between measured and predicted values of plough draught using three different values of cone indices were 0.93, 0.90 and 0.96 for median depth average, overall average and predicted cone indices, respectively. A regression analysis was also carried out between predicted and measured plough draught data and 92.31% of the data were explained by the following equation:

$$Dp = 1.015\ Dm \tag{7.16}$$

where: Dp and Dm are predicted and measured plough draught, using predicted values of cone indices (figure 7.28).

A similar explanation (92.68) was obtained between measured and predicted values of plough draught using the N.I.A.E. equation:

$$Dp = 0.99\ Dm \tag{7.17}$$

Plough draught was under-predicted by 1% and the correlation coefficient between measured and predicted values of plough draught was similar (0.96) to the one obtained for the E.S.C.A. equations (figure 7.29).

Slightly different patterns occurred in individual fields.

TABLE 7.24: PREDICTED AND MEASURED VALUES OF THE CONE IDECIES AND SPECIFIC PLOUGH DRAUGHT

	CONE INDEX KPA			SPECIFIC PLOUGH DRAUGHT KN		
	PREDICTED	MEASURED		MEASURED	PREDICTED	
REF		MEDIAN DEPTH AV	TOTAL AVERAGE		ESCA EQUATION	NIAE EQUATION
1	940.52	446.60	521.40	2.56	4.45	4.61
2	940.52	446.60	521.40	3.36	4.77	4.83
3	940.52	446.60	521.40	3.55	5.24	5.13
4	766.95	490.60	415.80	5.12	3.55	4.30
5	766.95	490.60	415.80	3.92	3.75	4.44
6	766.95	490.60	415.80	4.16	4.20	4.73
7	1071.15	510.40	464.20	3.89	5.11	4.74
8	1071.15	510.40	464.20	5.62	5.49	4.99
9	1071.15	510.40	464.20	5.80	5.69	5.12
10	940.52	446.60	521.40	3.22	4.35	4.58
11	940.52	446.60	521.40	3.61	4.49	4.77
12	940.52	446.60	521.40	4.99	4.66	5.00
13	768.85	490.60	415.80	3.15	3.57	4.39
14	768.85	490.60	415.80	3.15	3.71	4.57
15	768.85	490.60	415.80	3.98	3.92	4.85
16	1071.15	510.40	464.20	3.19	4.95	4.69
17	1071.15	510.40	464.20	3.98	5.10	4.88
18	1071.15	510.40	464.20	3.97	5.41	5.30
19	1022.66	125.40	90.20	4.44	4.73	4.59
20	1022.66	125.40	90.20	4.35	4.84	4.75
21	1022.66	125.40	90.20	5.45	5.02	4.98
22	1022.66	125.40	90.20	6.95	4.74	4.56
23	1022.66	125.40	90.20	6.77	4.87	4.64
24	1022.66	125.40	90.20	6.89	5.21	4.87
25	1057.74	462.00	413.60	3.44	4.99	4.70
26	1057.74	462.00	413.60	4.86	5.26	4.89
27	1057.74	462.00	413.60	6.16	6.17	5.48
28	1057.74	462.00	413.60	3.41	4.98	4.70
29	1057.74	462.00	413.60	4.10	5.25	4.88
30	1057.74	462.00	413.60	5.63	5.88	5.29
31	818.57	356.40	352.00	4.41	3.85	4.38
32	818.57	356.40	352.00	5.77	4.09	4.53
33	818.57	356.40	352.00	5.10	4.21	4.61
34	818.57	356.40	352.00	1.72	3.79	4.39
35	818.57	356.40	352.00	2.32	3.93	4.57
36	818.57	356.40	352.00	3.46	4.35	5.13
37	1057.74	462.00	413.60	2.22	4.92	4.72
38	1057.74	462.00	413.60	2.84	5.06	4.91
39	1057.74	462.00	413.60	3.21	5.66	5.71

TABLE 7.24 CONTINUED

	CONE INDEX KPA			SPECIFIC PLOUGH DRAUGHT KN		
	PREDICTED	MEASURED		MEASURED	PREDICTED	
REF		MEDIAN DEPTH AV	TOTAL AVERAGE		ESCA EQUATION	NIAE EQUATION
40	960.90	745.80	842.60	3.33	4.47	4.71
41	960.90	745.80	842.60	4.76	4.72	5.05
42	960.90	745.80	842.60	4.63	5.17	5.64
43	1143.55	662.20	624.80	4.68	5.31	4.42
44	1143.55	662.20	624.80	4.23	5.50	4.68
45	1143.55	662.20	624.80	5.78	5.76	5.02
46	1144.02	380.60	345.40	4.11	5.32	4.64
47	1144.02	380.60	345.40	4.48	5.49	4.87
48	1144.02	380.60	345.40	5.12	5.78	5.25
49	1143.55	662.20	624.80	3.91	5.26	4.33
50	1143.55	662.20	624.80	6.65	5.43	4.44
51	1143.55	662.20	624.80	7.09	5.92	4.76
52	960.90	745.80	842.60	4.49	4.47	4.65
53	960.90	745.80	842.60	4.77	4.76	4.85
54	960.90	745.80	842.60	5.58	5.28	5.19
55	1144.02	380.60	345.40	5.86	5.31	4.57
56	1144.02	380.60	345.40	6.05	5.57	4.74
57	1144.02	380.60	345.40	6.95	5.98	5.01
58	1019.10	356.40	286.00	2.36	4.78	4.59
59	1019.10	356.40	286.00	4.04	5.15	4.84
60	1019.10	356.40	286.00	4.63	5.69	5.19
61	1019.10	356.40	286.00	3.38	4.80	4.70
62	1019.10	356.40	286.00	3.30	5.04	5.02
63	1019.10	356.40	286.00	3.95	4.66	4.52
64	690.32	495.00	418.00	5.35	3.20	3.88
65	690.32	495.00	418.00	4.84	3.44	4.04
66	690.32	495.00	418.00	5.23	4.36	4.65
67	690.32	495.00	418.00	3.44	3.28	4.03
68	690.32	495.00	418.00	3.57	3.48	4.29
69	690.32	495.00	418.00	5.43	3.60	4.45

TABLE 7.24 CONTINUED

	CONE INDEX KPA			SPECIFIC PLOUGH DRAUGHT KN		
	PREDICTED	MEASURED		MEASURED	PREDICTED	
REF		MEDIAN DEPTH AV	TOTAL AVERAGE		ESCA EQUATION	NIAE EQUATION
70	954.16	393.80	345.40	3.07	4.45	4.63
71	954.16	393.80	345.40	4.14	4.61	4.85
72	954.16	393.80	345.40	4.86	4.94	5.29
73	1213.19	457.60	301.40	2.90	5.65	4.46
74	1213.19	457.60	301.40	1.62	5.84	4.70
75	1213.19	457.60	301.40	2.56	6.19	5.18
76	933.00	508.20	442.20	3.68	4.35	4.72
77	933.00	508.20	442.20	3.43	4.54	4.97
78	933.00	508.20	442.20	3.27	4.86	5.41
79	1130.00	413.60	248.60	3.68	5.20	4.57
80	1130.00	413.60	248.60	4.55	5.40	4.83
81	1130.00	413.60	248.60	5.23	5.66	5.18
82	1130.00	413.60	248.60	4.34	5.18	4.52
83	1130.00	413.60	248.60	4.99	5.43	4.69
84	1130.00	413.60	248.60	5.88	5.86	4.97
85	933.00	508.20	442.20	3.96	4.34	4.65
86	933.00	508.20	442.20	4.74	4.74	4.91
87	933.00	508.20	442.20	5.61	5.28	5.27
88	1213.19	457.60	301.40	3.66	5.60	4.34
89	1213.19	457.60	301.40	4.25	5.97	4.58
90	1213.19	457.60	301.40	6.22	6.50	4.94
91	954.16	393.80	345.40	4.60	4.43	4.56
92	954.16	393.80	345.40	4.47	4.87	4.85
93	954.16	393.80	345.40	6.38	4.93	4.89
94	741.96	479.60	374.00	4.10	3.51	3.93
95	741.96	479.60	374.00	4.57	3.87	4.17
96	741.96	479.60	374.00	5.17	4.41	4.52
97	741.96	479.60	374.00	5.64	3.46	3.95
98	741.96	479.60	374.00	4.24	3.64	4.19
99	741.96	479.60	374.00	7.45	3.64	4.19
100	666.70	664.40	618.20	2.26	3.11	3.94
101	666.70	664.40	618.20	3.32	3.22	4.09
102	666.70	664.40	618.20	3.06	3.53	4.50
103	666.70	664.40	618.20	3.73	3.19	3.95
104	666.70	664.40	618.20	4.25	3.54	4.18
105	666.70	664.40	618.20	4.81	4.20	4.61

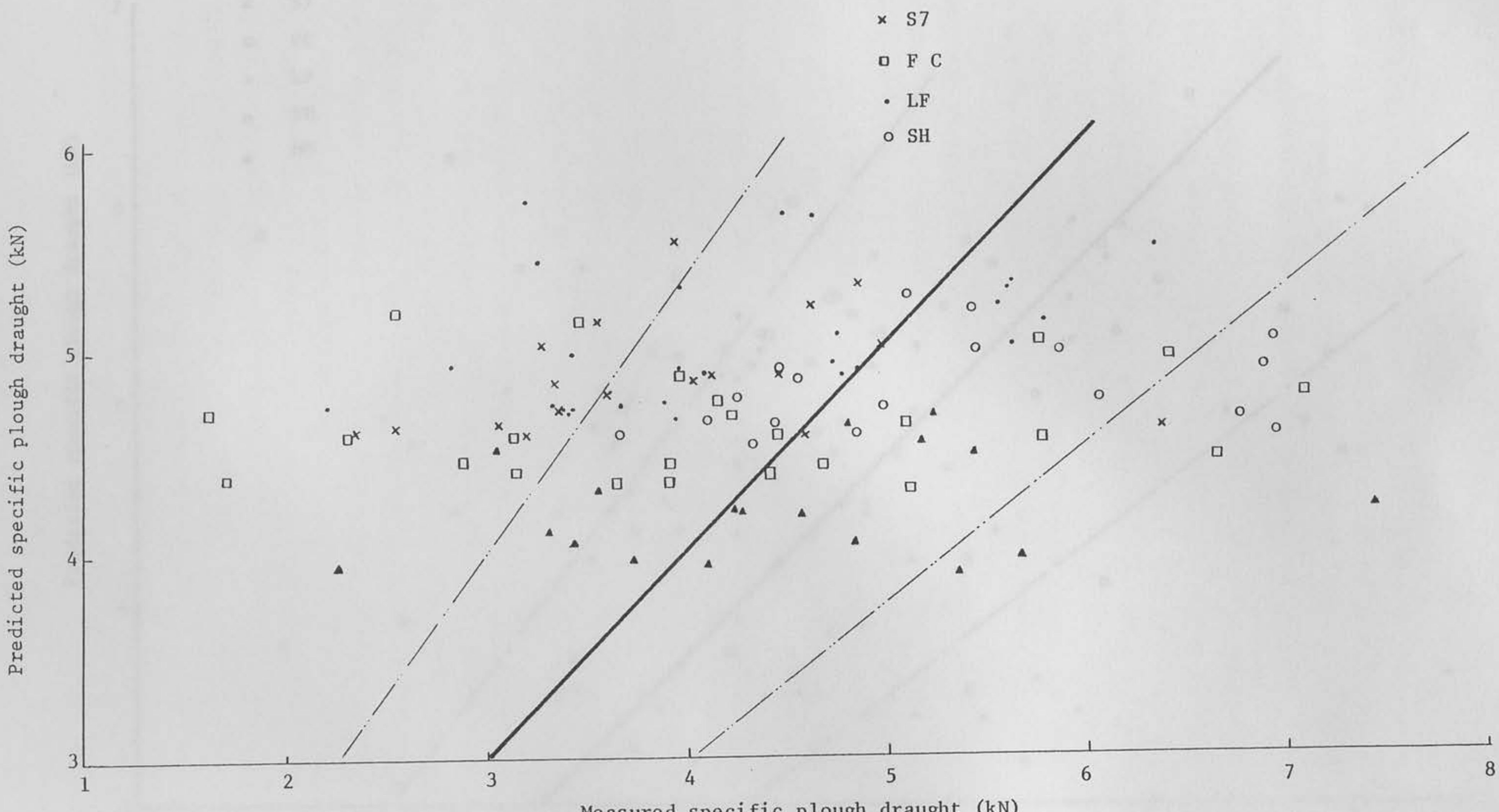

FIG. 7.28: Measured and predicted values of specific plough draught for different fields using the N.I.A.E. equation.

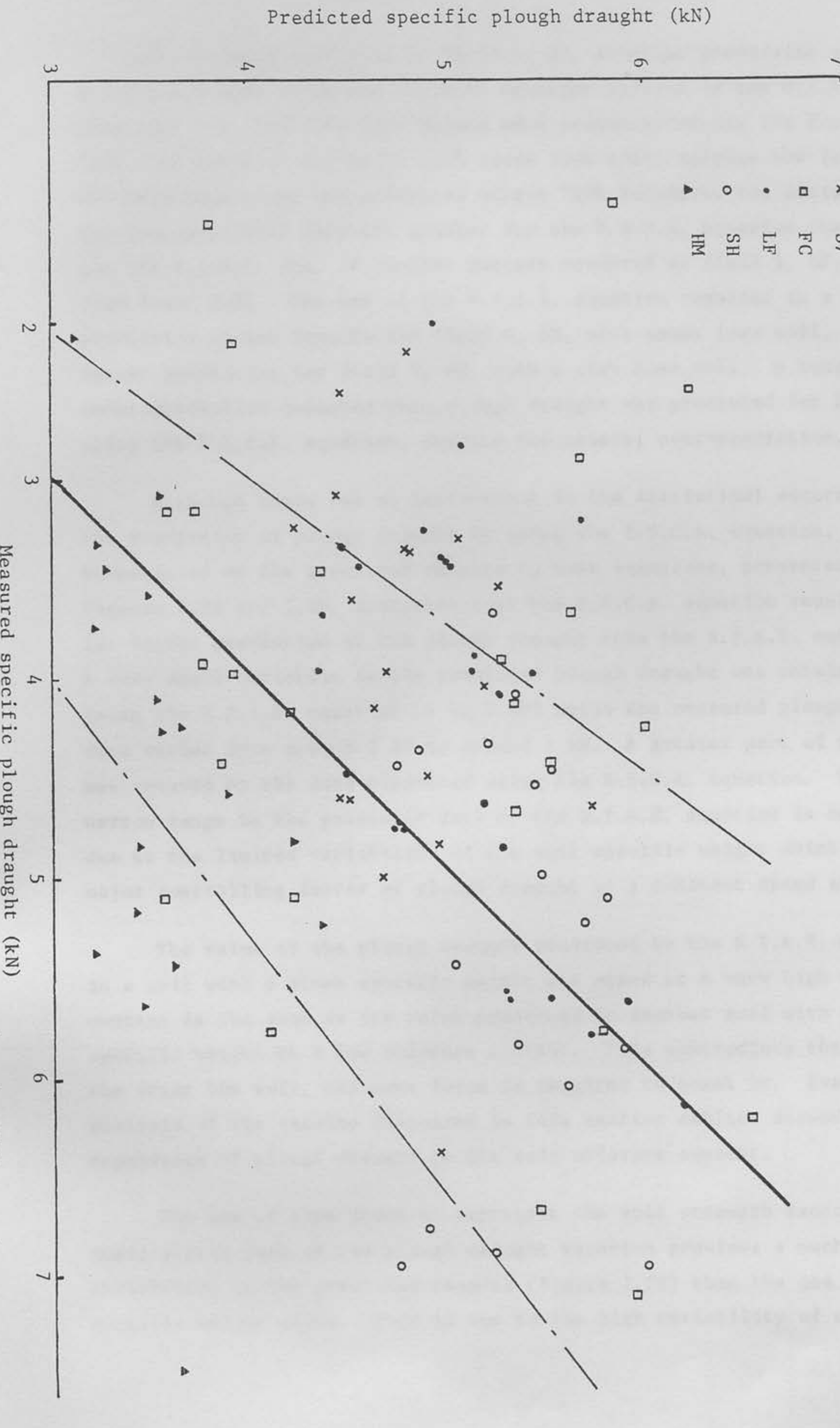

FIG. 7.29: Measured and predicted values of plough draught for various fields using the ESCA equation.

For a sandy loam soil at field 1, S7, a better prediction of plough draught was made using the E.S.C.A. equation instead of the N.I.A.E. equation, i.e. two more data points were predicted within the boundary of ±25%. At field 2, FC, again with sandy loam soil, despite the fact that one more data point was predicted within ±25% boundary, the deviation of the over-predicted data was greater for the E.S.C.A. equation than it was for the N.I.A.E. one. A similar pattern occurred at field 3, LF, with a clay loamy soil. The use of the N.I.A.E. equation resulted in a poorer prediction of the results for field 4, SH, with sandy loam soil, and better prediction for field 5, HM, with a clay loam soil. A considerable under-prediction occurred when plough draught was predicted for field 5 using the E.S.C.A. equation, despite the general over-prediction.

Although there was no improvement in the statistical accuracy of the prediction of plough draught by using the E.S.C.A. equation, visual examination of the predicted results by both equations, presented in figures 7.28 and 7.29, indicates that the E.S.C.A. equation results in a far better prediction of the plough draught than the N.I.A.E. equation. A very small variation in the predicted plough draught was obtained by using the N.I.A.E. equation (4 to 6 kN) while the measured plough draught data varied from around 2 kN to around 7 kN. A greater part of the range was covered by the data predicted using the E.S.C.A. equation. The narrow range in the predicted data by the N.I.A.E. equation is mainly due to the limited variability of the soil specific weight which is the major controlling factor of plough draught at a constant speed and depth.

The value of the plough draught predicted by the N.I.A.E. equation in a soil with a given specific weight and speed at a very high moisture content is the same as its value predicted in another soil with the same specific weight at a low moisture content. This contradicts the fact that the drier the soil, the more force is required to break it. Even the analysis of the results discussed in this section earlier showed considerable dependence of plough draught to the soil moisture content.

The use of cone index to represent the soil strength factor in the quasi static part of the plough draught equation provides a much wider variability on the predicted results (figure 7.29) than the use of soil specific weight alone. This is due to the high variability of cone index

(0-1000 kPa) as opposed to a very limited variation of soil bulk density or specific weight (1-1.8). There also exists a strong correlation between plough draught and cone indices in both the N.I.A.E. field data (section 7.4.1) and results of the field experiment carried out by the author. It is for these reasons that the E.S.C.A. equation is recommended for predicting the plough draught.

7.5 Workdays

The workday probability prediction programme (WDPP) was used to calculate the number of available days for tillage for two soil series, Macmerry and Winton at different probability levels and soil workability criteria (figures 7.30 and 7.31 and Table 7.25). The year was divided into four quarters, the first quarter commencing on 1st January. Initially ten different probability levels were chosen ranging from 0-100% but, later, three high probability levels of 80, 90 and 100% were found to be adequate. Of the ten different soil workability criteria, three were chosen, namely, 105, 110 and 115% of the soil moisture content at field capacity. These soil moisture levels are in the region of the soil moisture contents at the upper plasticity limits of 107 and 104% of field capacity for Macmerry and Winton soils, respectively, Table 7.26.

TABLE 7.25: Number of days available for tillage operations at varying probability levels and workability criteria in four quarters for Macmerry and Winton soils at Langhill.

SOIL WORKABILITY CRITERION % OF FC	NUMBER OF SOIL WORKABLE DAYS											
	1ST QUARTER			2ND QUARTER			3RD QUARTER			4TH QUARTER		
	PROBABILITY LEVEL %											
	80	90	100	80	90	100	80	90	100	80	90	100
	MACMERRY SOIL											
105	54	27	13	67	38	10	75	48	10	63	37	10
110	88	81	58	90	83	48	91	80	48	91	82	37
115	90	89	76	91	89	61	92	91	71	92	90	67
	WINTON SOIL											
105	12	4	1	22	7	2	24	14	4	17	3	1
110	83	65	32	88	66	35	80	72	31	88	71	26
115	89	87	70	91	88	52	91	90	61	92	90	57

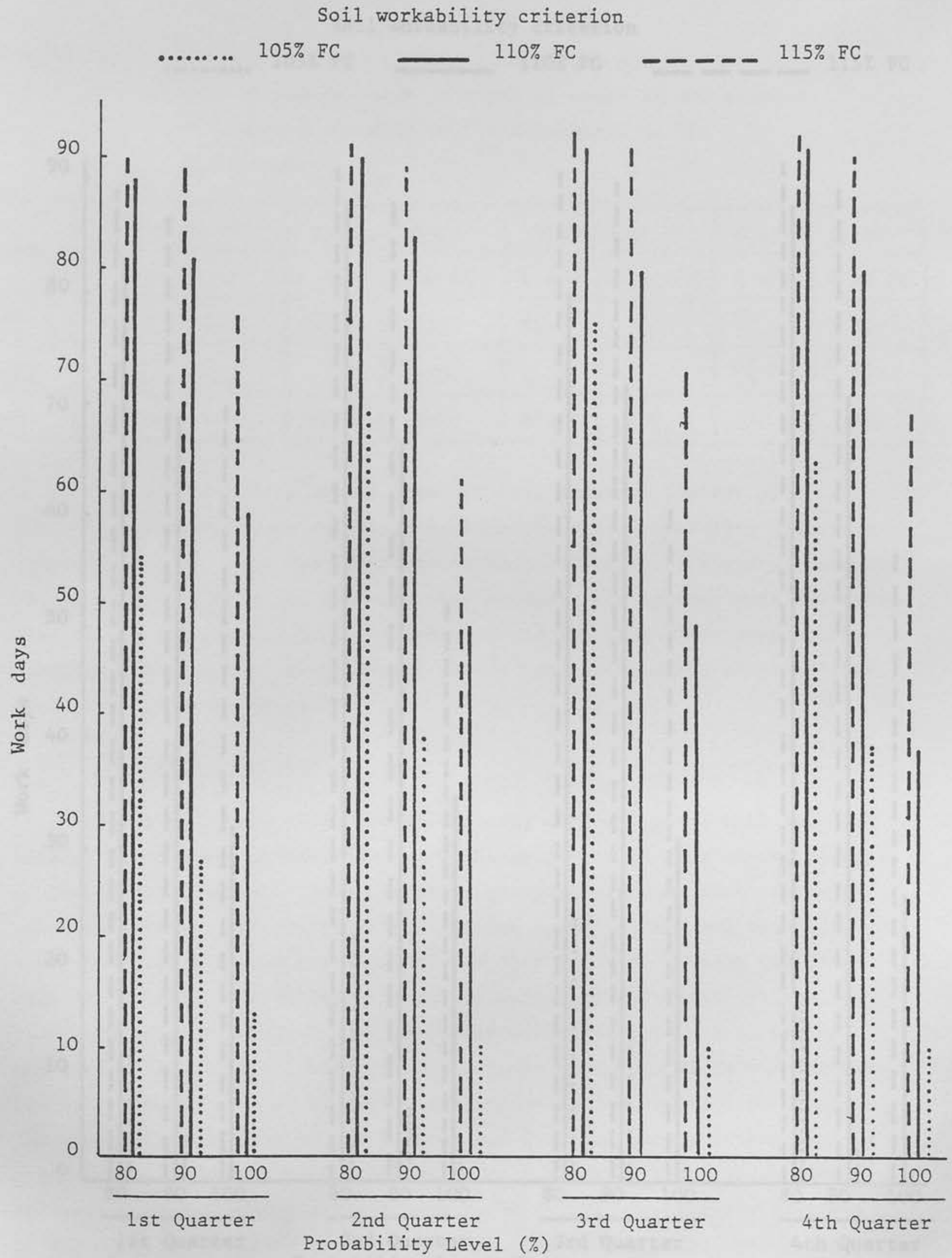

FIG. 7.30: Available days for tillage operations at varying probability level and soil workability criterion in four quarters for Macmerry soil series at Langhill.

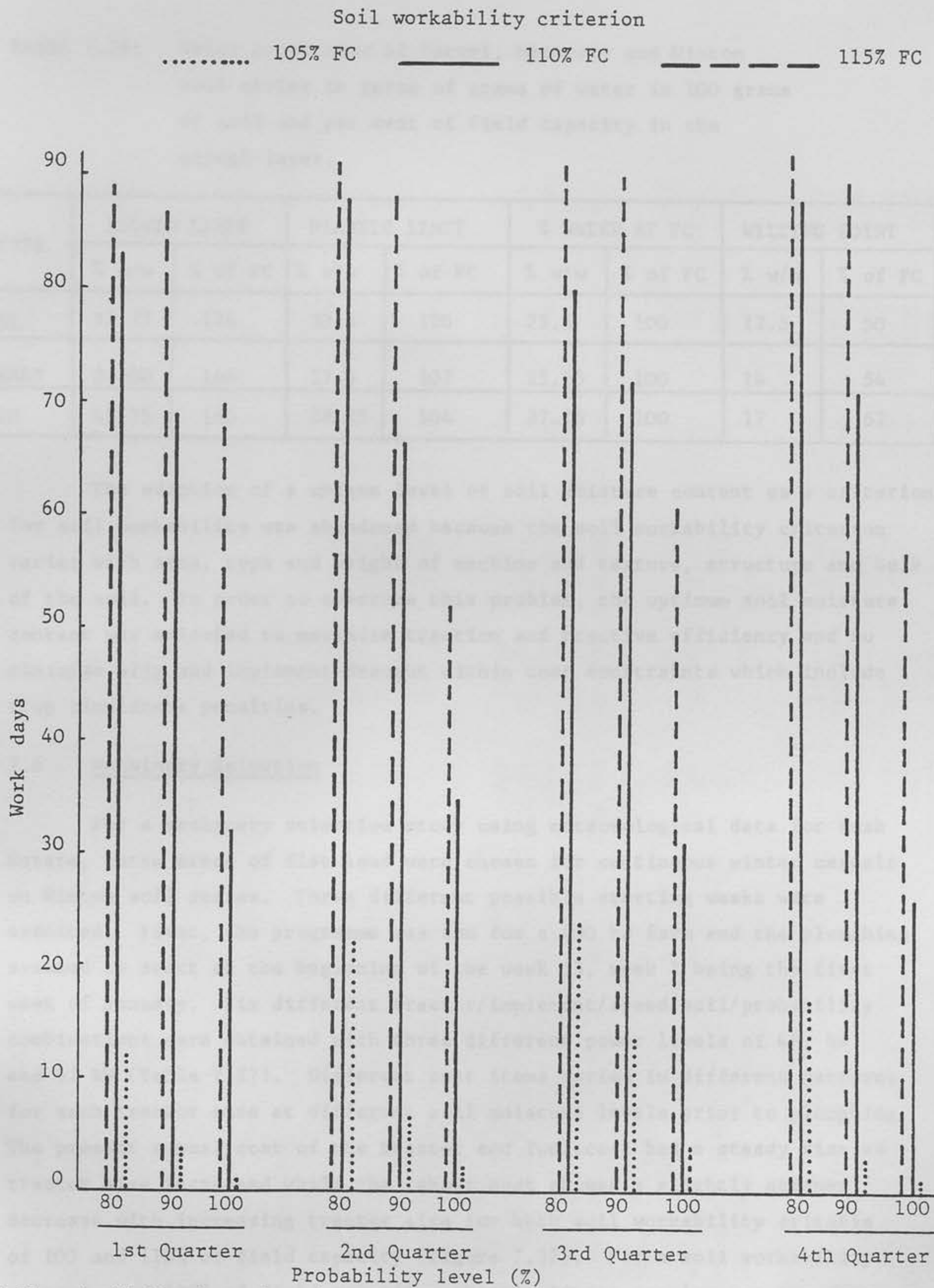

FIG. 7.31: Available days for tillage operations at varying probability level and soil workability criterion in four quarters for Winton soil series at Langhill.

TABLE 7.26: Water properties of Darvel, Macmerry and Winton soil series in terms of grams of water in 100 grams of soil and per cent of field capacity in the plough layer.

SOIL TYPE	LIQUID LIMIT		PLASTIC LIMIT		% WATER AT FC		WILTING POINT	
	% w/w	% of FC	% w/w	% of FC	% w/w	% of FC	% w/w	% of FC
DARVEL	32.75	128	30.5	120	25.5	100	12.5	50
MACMERRY	36.00	140	27.5	107	25.65	100	14	54
WINTON	43.75	160	28.25	104	27.15	100	17	62

The adoption of a unique level of soil moisture content as a criterion for soil workability was abandoned because the soil workability criterion varies with size, type and weight of machine and texture, structure and bulk of the soil. In order to overcome this problem, the optimum soil moisture content was selected to maximise traction and tractive efficiency and to minimise slip and implement draught within cost constraints which include crop timeliness penalties.

7.6 Machinery Selection

For a machinery selection study using meteorological data for Bush Estate, three areas of flat land were chosen for continuous winter cereals on Winton soil series. Three different possible starting weeks were examined. First, the programme was run for a 400 ha farm and the ploughing assumed to start at the beginning of the week 33, week 1 being the first week of January. Six different tractor/implement/speed/soil/probability combinations were obtained with three different power levels of 48, 64 and 91 kW (Table 7.27). Different cost items varied in different patterns for each tractor size at different soil moisture levels prior to ploughing. The present annual cost of the tractor and fuel cost had a steady rise as tractor size increased while the labour cost showed a slightly steeper decrease with increasing tractor size for both soil workability criteria of 105 and 110% of field capacity (figure 7.32). For a soil workability criterion of 105% of field capacity, the timeliness penalty was the same

TABLE 7.27: FEASIBLE TRACTOR-IPLEMENT COMBINATIONS FOR A 400 HA FARM
OPERATION STARTING AT WEEK 33 AND EXPECTED TO FINISH AT WEEK 42
PLOUGH OPERATING AT 80 % FIELD EFFICIENCY

	UNIT	COMBINATION NUMBER 1	2	3	4	5	6
TRACTOR SPECIFICATION							
POWER	KW	91	91	64	64	48	48
WEIGHT	KN	32	32	32	32	24	24
TRACTIVE EFFICIENCY	%	72	71	72	71	72	72
THEORETICAL PULL	KN	34.4	34.4	34.4	34.4	25.8	25.8
ACTUAL PULL	KN	24.8	24.8	24.8	24.8	18.7	18.6
SLIP	%	10	11	10	11	10	11
TYRE SIZE		18.4-38	18.4-38	18.4-38	18.4-38	18.4-34	18.4-34
PLOUGH SPECIFICATION							
PLOUGH DRAUGHT	KN	17.7	17.1	20.2	19.5	15.2	14.6
NUMBER OF PLOUGH BODIES		3	3	4	4	3	3
DEPTH OF CUT	M	0.30	0.30	0.30	0.30	0.30	0.30
WIDTH OF CUT	M	0.33	0.33	0.33	0.33	0.33	0.33
WORK RATE	HA/H	0.75	0.75	0.70	0.70	0.53	0.53
LATERAL DIRECTIONAL ANGLE	RAD.	0.62	0.62	0.62	0.62	0.62	0.62
SOIL SPECIFICATION							
WORKABILITY CRITERION	% FC	105	110	105	110	105	110
MOISTURE CONTENT	%W/W	30.08	31.51	30.08	31.51	30.08	31.51
CONE INDEX	KPA	858	820	858	820	858	820
SPECIFIC WEIGHT	KN/CM3	13.05	13.05	13.05	13.05	13.05	13.05
FIELD CAPACITY	MM	110.00	110.00	110.00	110.00	110.00	110.00
OPERATING CONDITIONS							
PROBABILITY LEVEL	%	90	100	90	100	90	100
TRAVEL SPEED	M/S	2.64	2.64	1.85	1.85	1.85	1.85
FINISHING WEEK NUMBER		43	42	43	43	48	46
NUMBER OF PENALTY WEEKS		1	0	1	1	6	4
COST OF OPERATION	POUNDS STERLING						
PLOUGH PURCHASE PRICE		1023	1023	1420	1420	1023	1023
TRACTOR PURCHASE PRICE		10857	10857	7743	7743	5898	5898
PRESENT ANNUAL COST OF TRACTOR		893	893	677	677	669	669
PRESENT ANNUAL COST OF PLOUGH		611	611	650	650	611	611
FUEL COST		828	828	629	629	625	625
LABOUR COST		1328	1328	1423	1423	1898	1898
TIMELINESS PENALTY		553	0	553	553	24902	10846
TOTAL COST OF THE SYSTEM		4213	3660	3932	3932	28705	14649

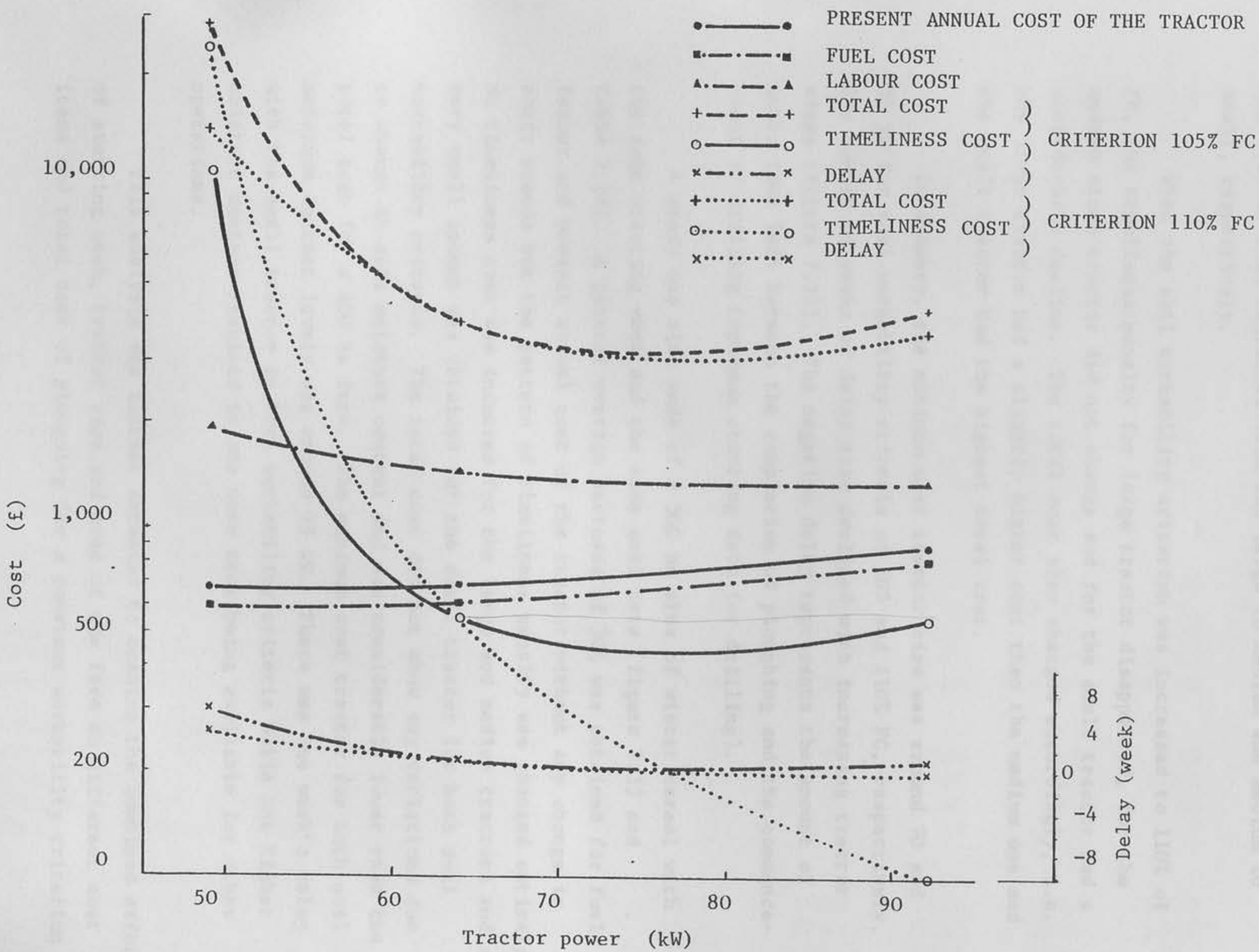

FIG. 7.32: Variations of different cost items with changing tractor power level at different soil workability criterion for a 400 ha farm.

for the large and medium size tractors, but had a sharp increase for the small tractor. Total cost increased marginally and rapidly when the tractor size decreased from the large to medium and medium to small, respectively.

When the soil workability criterion was increased to 110% of FC, the timeliness penalty for large tractor disappeared, for the medium sized tractor did not change and for the small tractor had a considerable decline. The total cost also changed accordingly, i.e. the large tractor had a slightly higher cost than the medium one and the small tractor had the highest total cost.

In summary, the minimum cost tractor size was around 70 and 85 kW for soil workability criteria of 105 and 110% FC, respectively. The number of weeks of delay also declined with increasing tractor sizes (figure 7.32). The negative delay represents the amount of extra time left between the completion of ploughing and the commence-:ment of drilling (optimum starting date for drilling).

A study was also made of a 300 ha area of winter cereal with the same starting week and the same soil data (figure 7.33 and Table 7.28). A general average decrease of 30% was obtained for fuel, labour and present annual cost of the tractor without any change in their trends but the pattern of timeliness penalty was changed entirely. No timeliness cost was incurred for the large and medium tractors and a very small amount was obtained for the small tractor for both soil workability criteria. The total cost did not show any variations due to change in soil moisture content and was considerably lower than the total cost for a 400 ha farm. The minimum cost tractor for both soil moisture content levels was around 75 kW. There was one week's delay with the small tractor in both workability criteria while the higher moisture content resulted in one more week being available for other operations.

This analysis was further extended to examine the combined effects of starting week, tractor size and area of the farm cn different cost items and total cost of ploughing for a constant workability criterion

TABLE 7.28: FEASIBLE TRACTOR-IPLEMENT COMBINATIONS FOR A 300 HA FARM OPERATION STARTING AT WEEK 33 AND EXPECTED TO FINISH AT WEEK 42 PLOUGH OPERATING AT 80 % FIELD EFFICIENCY

	UNIT	COMBINATION NUMBER 1	2	3	4	5	6
TRACTOR SPECIFICATION							
POWER	KW	91	91	64	64	48	48
WEIGHT	KN	32	32	32	32	24	24
TRACTIVE EFFICIENCY	%	72	71	72	71	72	72
THEORETICAL PULL	KN	34.4	34.4	34.4	34.4	25.8	25.8
ACTUAL PULL	KN	24.8	24.8	24.8	24.8	18.7	18.6
SLIP	%	10	11	10	11	10	11
TYRE SIZE		18.4-38	18.4-38	18.4-38	18.4-38	18.4-34	18.4-34
PLOUGH SPECIFICATION							
PLOUGH DRAUGHT	KN	17.7	17.1	20.2	19.5	15.2	14.6
NUMBER OF PLOUGH BODIES		3	3	4	4	3	3
DEPTH OF CUT	M	0.30	0.30	0.30	0.30	0.30	0.30
WIDTH OF CUT	M	0.33	0.33	0.33	0.33	0.33	0.33
WORK RATE	HA/H	0.75	0.75	0.70	0.70	0.53	0.53
LATERAL DIRECTIONAL ANGLE	RAD.	0.62	0.62	0.62	0.62	0.62	0.62
SOIL SPECIFICATION							
WORKABILITY CRITERION	% FC	105	110	105	110	105	110
MOISTURE CONTENT	%W/W	30.08	31.51	30.08	31.51	30.08	31.51
CONE INDEX	KPA	858	820	858	820	858	820
SPECIFIC WEIGHT	KN/CM3	13.05	13.05	13.05	13.05	13.05	13.05
FIELD CAPACITY	MM	110.00	110.00	110.00	110.00	110.00	110.00
OPERATING CONDITIONS							
PROBABILITY LEVEL	%	90	100	90	100	90	100
TRAVEL SPEED	M/S	2.64	2.64	1.85	1.85	1.85	1.85
FINISHING WEEK NUMBER		40	39	41	40	43	43
NUMBER OF PENALTY WEEKS		-2	-3	-1	-2	1	1
COST OF OPERATION POUNDS STERLING							
PLOUGH PURCHASE PRICE		1023	1023	1420	1420	1023	1023
TRACTOR PURCHASE PRICE		10857	10857	7743	7743	5898	5898
PRESENT ANNUAL COST OF TRACTOR		691	691	524	524	516	516
PRESENT ANNUAL COST OF PLOUGH		468	468	499	499	468	468
FUEL COST		621	621	472	472	468	468
LABOUR COST		996	996	1067	1067	1423	1423
TIMELINESS PENALTY		0	0	0	0	414	414
TOTAL COST OF THE SYSTEM		2776	2776	2562	2562	3289	3289

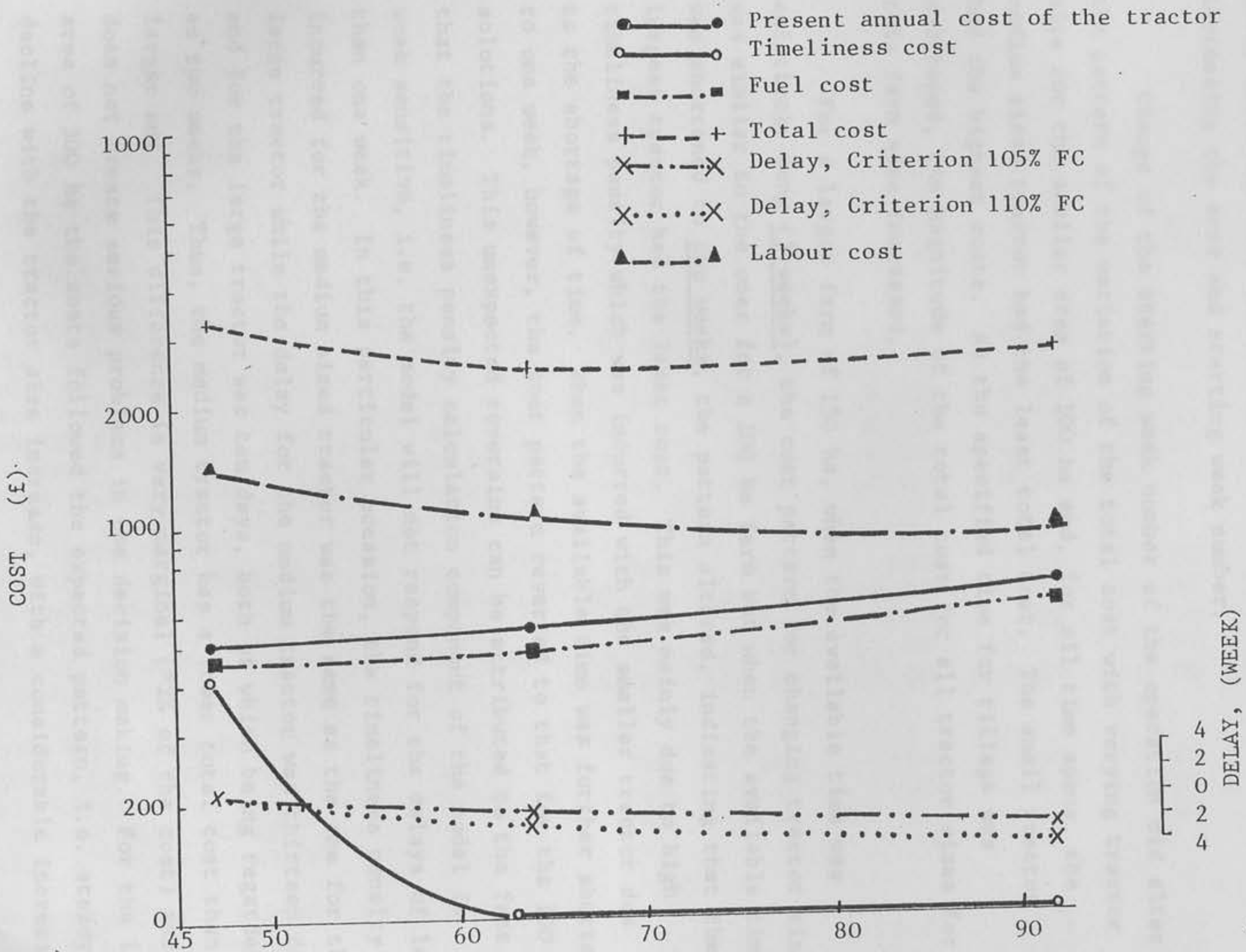

FIG. 7.33: Variation of different cost items with changing tractor power level at different soil workability criteria for a 300 ha farm.

of 105% FC and design probability of 90% (figure 7.34) and Tables 7.29 - 7.38. The pattern of the change of fuel, labour and present annual cost of the tractor with changing tractor size and starting week number, did not vary from the two previous occasions but their magnitude increased as the area was increased. Timeliness costs decreased with increasing tractor size and increased with increasing the area and starting week number.

Change of the starting week number of the operation did alter the pattern of the variation of the total cost with varying tractor size for the smaller area of 100 ha and, for all time spans, the medium sized tractor had the least total cost. The small tractor had the highest costs. As the specified time for tillage was shortened, the magnitude of the total cost for all tractor sizes for this farm size increased.

For a larger farm of 150 ha, when the available time was relatively long (3 weeks), the cost pattern for changing tractor size was similar to the ones for a 100 ha farm but when the available time was shortened to two weeks, the pattern altered, indicating that the largest tractor had the least cost. This was mainly due to high timeliness penalty which was incurred with the smaller tractor due to the shortage of time. When the available time was further shortened to one week, however, the cost pattern reverted to that for the 100 ha solutions. This unexpected reversion can be attributed to the fact that the timeliness penalty calculation component of the model is week sensitive, i.e. the model will not respond for the delays of less than one week. In this particular occasion, the timeliness penalty incurred for the medium sized tractor was the same as the one for the large tractor while the delay for the medium tractor was thirteen days and for the large tractor was ten days, both of which being regarded as two weeks. Thus, the medium tractor has a lower total cost than the larger one. This difference is very marginal ($\pm 2\%$ of the cost) and does not create serious problems in the decision making. For the larger area of 300 ha the costs followed the expected pattern, i.e. steady decline with the tractor size increase, with a considerable increase on

TABLE 7.29: FEASIBLE TRACTOR-IPLEMENT COMBINATIONS FOR A 100 HA FARM
OPERATION STARTING AT WEEK 39 AND EXPECTED TO FINISH AT WEEK 42
PLOUGH OPERATING AT 80 % FIELD EFFICIENCY

	UNIT	COMBINATION NUMBER 1	2	3	4	5	6
TRACTOR SPECIFICATION							
POWER	KW	91	91	64	64	48	48
WEIGHT	KN	32	32	32	32	24	24
TRACTIVE EFFICIENCY	%	72	71	72	71	72	72
THEORETICAL PULL	KN	34.4	34.4	34.4	34.4	25.8	25.8
ACTUAL PULL	KN	24.8	24.8	24.8	24.8	18.7	18.6
SLIP	%	10	11	10	11	10	11
TYRE SIZE		18.4-38	18.4-38	18.4-38	18.4-38	18.4-34	18.4-34
PLOUGH SPECIFICATION							
PLOUGH DRAUGHT	KN	17.7	17.1	20.2	19.5	15.2	14.6
NUMBER OF PLOUGH BODIES		3	3	4	4	3	3
DEPTH OF CUT	M	0.30	0.30	0.30	0.30	0.30	0.30
WIDTH OF CUT	M	0.33	0.33	0.33	0.33	0.33	0.33
WORK RATE	HA/H	0.75	0.75	0.70	0.70	0.53	0.53
LATERAL DIRECTIONAL ANGLE	RAD.	0.62	0.62	0.62	0.62	0.62	0.62
SOIL SPECIFICATION							
WORKABILITY CRITERION	% FC	105	110	105	110	105	110
MOISTURE CONTENT	%W/W	30.08	31.51	30.08	31.51	30.08	31.51
CONE INDEX	KPA	858	820	858	820	858	820
SPECIFIC WEIGHT	KN/CM3	13.05	13.05	13.05	13.05	13.05	13.05
FIELD CAPACITY	MM	110.00	110.00	110.00	110.00	110.00	110.00
OPERATING CONDITIONS							
PROBABILITY LEVEL	%	90	100	100	100	90	100
TRAVEL SPEED	M/S	2.64	2.64	1.85	1.85	1.85	1.85
FINISHING WEEK NUMBER		41	41	42	41	42	42
NUMBER OF PENALTY WEEKS		-1	-1	0	-1	0	0
COST OF OPERATION POUNDS STERLING							
PLOUGH PURCHASE PRICE		1023	1023	1420	1420	1023	1023
TRACTOR PURCHASE PRICE		10857	10857	7743	7743	5898	5898
PRESENT ANNUAL COST OF TRACTOR		254	254	193	193	192	192
PRESENT ANNUAL COST OF PLOUGH		177	177	193	193	177	177
FUEL COST		207	207	157	157	156	156
LABOUR COST		332	332	355	355	474	474
TIMELINESS PENALTY		0	0	0	0	0	0
TOTAL COST OF THE SYSTEM		970	970	898	898	999	999

TABLE 7.30: FEASIBLE TRACTOR-IPLEMENT COMBINATIONS FOR A 100 HA FARM
OPERATION STARTING AT WEEK 40 AND EXPECTED TO FINISH AT WEEK 42
PLOUGH OPERATING AT 80 % FIELD EFFICIENCY

	UNIT	COMBINATION NUMBER 1	2	3	4	5	6
TRACTOR SPECIFICATION							
POWER	KW	91	91	64	64	48	48
WEIGHT	KN	32	32	32	32	24	24
TRACTIVE EFFICIENCY	%	72	71	72	71	72	72
THEORETICAL PULL	KN	34.4	34.4	34.4	34.4	25.8	25.8
ACTUAL PULL	KN	24.8	24.8	24.8	24.8	18.7	18.6
SLIP	%	10	11	10	11	10	11
TYRE SIZE		18.4-38	18.4-38	18.4-38	18.4-38	18.4-34	18.4-34
PLOUGH SPECIFICATION							
PLOUGH DRAUGHT	KN	17.7	17.1	20.2	19.5	15.2	14.6
NUMBER OF PLOUGH BODIES		3	3	4	4	3	3
DEPTH OF CUT	M	0.30	0.30	0.30	0.30	0.30	0.30
WIDTH OF CUT	M	0.33	0.33	0.33	0.33	0.33	0.33
WORK RATE	HA/H	0.75	0.75	0.70	0.70	0.53	0.53
LATERAL DIRECTIONAL ANGLE	RAD.	0.62	0.62	0.62	0.62	0.62	0.62
SOIL SPECIFICATION							
WORKABILITY CRITERION	% FC	105	110	105	110	105	110
MOISTURE CONTENT	%W/W	30.08	31.51	30.08	31.51	30.08	31.51
CONE INDEX	KPA	858	820	858	820	858	820
SPECIFIC WEIGHT	KN/CM3	13.05	13.05	13.05	13.05	13.05	13.05
FIELD CAPACITY	MM	110.00	110.00	110.00	110.00	110.00	110.00
OPERATING CONDITIONS							
PROBABILITY LEVEL	%	90	100	90	100	90	100
TRAVEL SPEED	M/S	2.64	2.64	1.85	1.85	1.85	1.85
FINISHING WEEK NUMBER		42	42	42	42	43	43
NUMBER OF PENALTY WEEKS		0	0	0	0	1	1
COST OF OPERATION POUNDS STERLING							
PLOUGH PURCHASE PRICE		1023	1023	1420	1420	1023	1023
TRACTOR PURCHASE PRICE		10857	10857	7743	7743	5898	5898
PRESENT ANNUAL COST OF TRACTOR		254	254	193	193	192	192
PRESENT ANNUAL COST OF PLOUGH		177	177	193	193	177	177
FUEL COST		207	207	157	157	156	156
LABOUR COST		332	332	355	355	474	474
TIMELINESS PENALTY		0	0	0	0	138	138
TOTAL COST OF THE SYSTEM		970	970	898	898	1137	1137

TABLE 7.31: FEASIBLE TRACTOR-IPLEMENT COMBINATIONS FOR A 100 HA FARM
OPERATION STARTING AT WEEK 41 AND EXPECTED TO FINISH AT WEEK 42
PLOUGH OPERATING AT 80 % FIELD EFFICIENCY

	UNIT	COMBINATION NUMBER 1	2	3	4	5	6
TRACTOR SPECIFICATION							
POWER	KW	91	91	64	64	48	48
WEIGHT	KN	32	32	32	32	24	24
TRACTIVE EFFICIENCY	%	72	71	72	71	72	72
THEORETICAL PULL	KN	34.4	34.4	34.4	34.4	25.8	25.8
ACTUAL PULL	KN	24.8	24.8	24.8	24.8	18.7	18.6
SLIP	%	10	11	10	11	10	11
TYRE SIZE		18.4-38	18.4-38	18.4-38	18.4-38	18.4-34	18.4-34
PLOUGH SPECIFICATION							
PLOUGH DRAUGHT	KN	17.7	17.1	20.2	19.5	15.2	14.6
NUMBER OF PLOUGH BODIES		3	3	4	4	3	3
DEPTH OF CUT	M	0.30	0.30	0.30	0.30	0.30	0.30
WIDTH OF CUT	M	0.33	0.33	0.33	0.33	0.33	0.33
WORK RATE	HA/H	0.75	0.75	0.70	0.70	0.53	0.53
LATERAL DIRECTIONAL ANGLE	RAD.	0.62	0.62	0.62	0.62	0.62	0.62
SOIL SPECIFICATION							
WORKABILITY CRITERION	% FC	105	110	105	110	105	110
MOISTURE CONTENT	%W/W	30.08	31.51	30.08	31.51	30.08	31.51
CONE INDEX	KPA	858	820	858	820	858	820
SPECIFIC WEIGHT	KN/CM3	13.05	13.05	13.05	13.05	13.05	13.05
FIELD CAPACITY	MM	110.00	110.00	110.00	110.00	110.00	110.00
OPERATING CONDITIONS							
PROBABILITY LEVEL	%	100	100	100	100	100	100
TRAVEL SPEED	M/S	2.64	2.64	1.85	1.85	1.85	1.85
FINISHING WEEK NUMBER		43	43	43	43	44	44
NUMBER OF PENALTY WEEKS		1	1	1	1	2	2
COST OF OPERATION POUNDS STERLING							
PLOUGH PURCHASE PRICE		1023	1023	1420	1420	1023	1023
TRACTOR PURCHASE PRICE		10857	10857	7743	7743	5898	5898
PRESENT ANNUAL COST OF TRACTOR		254	254	193	193	192	192
PRESENT ANNUAL COST OF PLOUGH		177	177	193	193	177	177
FUEL COST		207	207	157	157	156	156
LABOUR COST		332	332	355	355	474	474
TIMELINESS PENALTY		138	138	138	138	636	636
TOTAL COST OF THE SYSTEM		1108	1108	1036	1036	1635	1635

TABLE 7.32: FEASIBLE TRACTOR-IPLEMENT COMBINATIONS FOR A 150 HA FARM
OPERATION STARTING AT WEEK 39 AND EXPECTED TO FINISH AT WEEK 42
PLOUGH OPERATING AT 80 % FIELD EFFICIENCY

	UNIT	COMBINATION NUMBER 1	2	3	4	5	6
TRACTOR SPECIFICATION							
POWER	KW	91	91	64	64	48	48
WEIGHT	KN	32	32	32	32	24	24
TRACTIVE EFFICIENCY	%	72	71	72	71	72	72
THEORETICAL PULL	KN	34.4	34.4	34.4	34.4	25.8	25.8
ACTUAL PULL	KN	24.8	24.8	24.8	24.8	18.7	18.6
SLIP	%	10	11	10	11	10	11
TYRE SIZE		18.4-38	18.4-38	18.4-38	18.4-38	18.4-34	18.4-34
PLOUGH SPECIFICATION							
PLOUGH DRAUGHT	KN	17.7	17.1	20.2	19.5	15.2	14.6
NUMBER OF PLOUGH BODIES		3	3	4	4	3	3
DEPTH OF CUT	M	0.30	0.30	0.30	0.30	0.30	0.30
WIDTH OF CUT	M	0.33	0.33	0.33	0.33	0.33	0.33
WORK RATE	HA/H	0.75	0.75	0.70	0.70	0.53	0.53
LATERAL DIRECTIONAL ANGLE	RAD.	0.62	0.62	0.62	0.62	0.62	0.62
SOIL SPECIFICATION							
WORKABILITY CRITERION	% FC	105	110	105	110	105	110
MOISTURE CONTENT	%W/W	30.08	31.51	30.08	31.51	30.08	31.51
CONE INDEX	KPA	858	820	858	820	858	820
SPECIFIC WEIGHT	KN/CM3	13.05	13.05	13.05	13.05	13.05	13.05
FIELD CAPACITY	MM	110.00	110.00	110.00	110.00	110.00	110.00
OPERATING CONDITIONS							
PROBABILITY LEVEL	%	100	100	90	100	90	100
TRAVEL SPEED	M/S	2.64	2.64	1.85	1.85	1.85	1.85
FINISHING WEEK NUMBER		43	42	43	42	44	43
NUMBER OF PENALTY WEEKS		1	0	1	0	2	1
COST OF OPERATION POUNDS STERLING							
PLOUGH PURCHASE PRICE		1023	1023	1420	1420	1023	1023
TRACTOR PURCHASE PRICE		10857	10857	7743	7743	5898	5898
PRESENT ANNUAL COST OF TRACTOR		370	370	281	281	278	278
PRESENT ANNUAL COST OF PLOUGH		249	249	269	269	249	249
FUEL COST		310	310	236	236	234	234
LABOUR COST		498	498	533	533	711	711
TIMELINESS PENALTY		207	0	207	0	954	207
TOTAL COST OF THE SYSTEM		1634	1427	1526	1319	2426	1679

TABLE 7.33: FEASIBLE TRACTOR-IPLEMENT COMBINATIONS FOR A 150 HA FARM
OPERATION STARTING AT WEEK 40 AND EXPECTED TO FINISH AT WEEK 42
PLOUGH OPERATING AT 80 % FIELD EFFICIENCY

	UNIT	COMBINATION NUMBER 1	2	3	4	5	6
TRACTOR SPECIFICATION							
POWER	KW	91	91	64	64	48	48
WEIGHT	KN	32	32	32	32	24	24
TRACTIVE EFFICIENCY	%	72	71	72	71	72	72
THEORETICAL PULL	KN	34.4	34.4	34.4	34.4	25.8	25.8
ACTUAL PULL	KN	24.8	24.8	24.8	24.8	18.7	18.6
SLIP	%	10	11	10	11	10	11
TYRE SIZE		18.4-38	18.4-38	18.4-38	18.4-38	18.4-34	18.4-34
PLOUGH SPECIFICATION							
PLOUGH DRAUGHT	KN	17.7	17.1	20.2	19.5	15.2	14.6
NUMBER OF PLOUGH BODIES		3	3	4	4	3	3
DEPTH OF CUT	M	0.30	0.30	0.30	0.30	0.30	0.30
WIDTH OF CUT	M	0.33	0.33	0.33	0.33	0.33	0.33
WORK RATE	HA/H	0.75	0.75	0.70	0.70	0.53	0.53
LATERAL DIRECTIONAL ANGLE	RAD.	0.62	0.62	0.62	0.62	0.62	0.62
SOIL SPECIFICATION							
WORKABILITY CRITERION	% FC	105	110	105	110	105	110
MOISTURE CONTENT	%W/W	30.08	31.51	30.08	31.51	30.08	31.51
CONE INDEX	KPA	858	820	858	820	858	820
SPECIFIC WEIGHT	KN/CM3	13.05	13.05	13.05	13.05	13.05	13.05
FIELD CAPACITY	MM	110.00	110.00	110.00	110.00	110.00	110.00
OPERATING CONDITIONS							
PROBABILITY LEVEL	%	90	100	100	100	90	100
TRAVEL SPEED	M/S	2.64	2.64	1.85	1.85	1.85	1.85
FINISHING WEEK NUMBER		43	43	44	43	45	44
NUMBER OF PENALTY WEEKS		1	1	2	1	3	2
COST OF OPERATION POUNDS STERLING							
PLOUGH PURCHASE PRICE		1023	1023	1420	1420	1023	1023
TRACTOR PURCHASE PRICE		10857	10857	7743	7743	5898	5898
PRESENT ANNUAL COST OF TRACTOR		370	370	281	281	278	278
PRESENT ANNUAL COST OF PLOUGH		249	249	269	269	249	249
FUEL COST		310	310	236	236	234	234
LABOUR COST		498	498	533	533	711	711
TIMELINESS PENALTY		207	207	954	207	2241	954
TOTAL COST OF THE SYSTEM		1634	1634	2273	1526	3713	2426

TABLE 7.34: FEASIBLE TRACTOR-IPLEMENT COMBINATIONS FOR A 150 HA FARM
OPERATION STARTING AT WEEK 41 AND EXPECTED TO FINISH AT WEEK 42
PLOUGH OPERATING AT 80 % FIELD EFFICIENCY

	UNIT	COMBINATION NUMBER 1	2	3	4	5	6
TRACTOR SPECIFICATION							
POWER	KW	91	91	64	64	48	48
WEIGHT	KN	32	32	32	32	24	24
TRACTIVE EFFICIENCY	%	72	71	72	71	72	72
THEORETICAL PULL	KN	34.4	34.4	34.4	34.4	25.8	25.8
ACTUAL PULL	KN	24.8	24.8	24.8	24.8	18.7	18.6
SLIP	%	10	11	10	11	10	11
TYRE SIZE		18.4-38	18.4-38	18.4-38	18.4-38	18.4-34	18.4-34
PLOUGH SPECIFICATION							
PLOUGH DRAUGHT	KN	17.7	17.1	20.2	19.5	15.2	14.6
NUMBER OF PLOUGH BODIES		3	3	4	4	3	3
DEPTH OF CUT	M	0.30	0.30	0.30	0.30	0.30	0.30
WIDTH OF CUT	M	0.33	0.33	0.33	0.33	0.33	0.33
WORK RATE	HA/H	0.75	0.75	0.70	0.70	0.53	0.53
LATERAL DIRECTIONAL ANGLE	RAD.	0.62	0.62	0.62	0.62	0.62	0.62
SOIL SPECIFICATION							
WORKABILITY CRITERION	% FC	105	110	105	110	105	110
MOISTURE CONTENT	%W/W	30.08	31.51	30.08	31.51	30.08	31.51
CONE INDEX	KPA	858	820	858	820	858	820
SPECIFIC WEIGHT	KN/CM3	13.05	13.05	13.05	13.05	13.05	13.05
FIELD CAPACITY	MM	110.00	110.00	110.00	110.00	110.00	110.00
OPERATING CONDITIONS							
PROBABILITY LEVEL	%	100	100	90	100	90	100
TRAVEL SPEED	M/S	2.64	2.64	1.85	1.85	1.85	1.85
FINISHING WEEK NUMBER		44	44	44	44	46	45
NUMBER OF PENALTY WEEKS		2	2	2	2	4	3
COST OF OPERATION POUNDS STERLING							
PLOUGH PURCHASE PRICE		1023	1023	1420	1420	1023	1023
TRACTOR PURCHASE PRICE		10857	10857	7743	7743	5898	5898
PRESENT ANNUAL COST OF TRACTOR		370	370	281	281	278	278
PRESENT ANNUAL COST OF PLOUGH		249	249	269	269	249	249
FUEL COST		310	310	236	236	234	234
LABOUR COST		498	498	533	533	711	711
TIMELINESS PENALTY		954	954	954	954	4067	2241
TOTAL COST OF THE SYSTEM		2381	2381	2273	2273	5539	3713

TABLE 7.35: FEASIBLE TRACTOR-IPLEMENT COMBINATIONS FOR A 300 HA FARM
OPERATION STARTING AT WEEK 39 AND EXPECTED TO FINISH AT WEEK 42
PLOUGH OPERATING AT 80 % FIELD EFFICIENCY

	UNIT	COMBINATION NUMBER 1	2	3	4	5
TRACTOR SPECIFICATION						
POWER	KW	91	91	64	64	48
WEIGHT	KN	32	32	32	32	24
TRACTIVE EFFICIENCY	%	72	71	72	71	72
THEORETICAL PULL	KN	34.4	34.4	34.4	34.4	25.8
ACTUAL PULL	KN	24.8	24.8	24.8	24.8	18.6
SLIP	%	10	11	10	11	11
TYRE SIZE		18.4-38	18.4-38	18.4-38	18.4-38	18.4-34
PLOUGH SPECIFICATION						
PLOUGH DRAUGHT	KN	17.7	17.1	20.2	19.5	14.6
NUMBER OF PLOUGH BODIES		3	3	4	4	3
DEPTH OF CUT	M	0.30	0.30	0.30	0.30	0.30
WIDTH OF CUT	M	0.33	0.33	0.33	0.33	0.33
WORK RATE	HA/H	0.75	0.75	0.70	0.70	0.53
LATERAL DIRECTIONAL ANGLE	RAD.	0.62	0.62	0.62	0.62	0.62
SOIL SPECIFICATION						
WORKABILITY CRITERION	% FC	105	110	105	110	110
MOISTURE CONTENT	%W/W	30.08	31.51	30.08	31.51	31.51
CONE INDEX	KPA	858	820	858	820	820
SPECIFIC WEIGHT	KN/CM3	13.05	13.05	13.05	13.05	13.05
FIELD CAPACITY	MM	110.00	110.00	110.00	110.00	110.00
OPERATING CONDITIONS						
PROBABILITY LEVEL	%	90	100	90	100	100
TRAVEL SPEED	M/S	2.64	2.64	1.85	1.85	1.85
FINISHING WEEK NUMBER		48	45	48	46	49
NUMBER OF PENALTY WEEKS		6	3	6	4	7
COST OF OPERATION POUNDS STERLING						
PLOUGH PURCHASE PRICE		1023	1023	1420	1420	1023
TRACTOR PURCHASE PRICE		10857	10857	7743	7743	5898
PRESENT ANNUAL COST OF TRACTOR		691	691	524	524	516
PRESENT ANNUAL COST OF PLOUGH		468	468	499	499	468
FUEL COST		621	621	472	472	468
LABOUR COST		996	996	1067	1067	1423
TIMELINESS PENALTY		18676	4482	18676	8134	25566
TOTAL COST OF THE SYSTEM		21452	7258	21238	10696	28441

TABLE 7.36: FEASIBLE TRACTOR-IPLEMENT COMBINATIONS FOR A 300 HA FARM
OPERATION STARTING AT WEEK 40 AND EXPECTED TO FINISH AT WEEK 42
PLOUGH OPERATING AT 80 % FIELD EFFICIENCY

	UNIT	COMBINATION NUMBER 1	2	3	4	5
TRACTOR SPECIFICATION						
POWER	KW	91	91	64	64	48
WEIGHT	KN	32	32	32	32	24
TRACTIVE EFFICIENCY	%	72	71	72	71	72
THEORETICAL PULL	KN	34.4	34.4	34.4	34.4	25.8
ACTUAL PULL	KN	24.8	24.8	24.8	24.8	18.6
SLIP	%	10	11	10	11	11
TYRE SIZE		18.4-38	18.4-38	18.4-38	18.4-38	18.4-34
PLOUGH SPECIFICATION						
PLOUGH DRAUGHT	KN	17.7	17.1	20.2	19.5	14.6
NUMBER OF PLOUGH BODIES		3	3	4	4	3
DEPTH OF CUT	M	0.30	0.30	0.30	0.30	0.30
WIDTH OF CUT	M	0.33	0.33	0.33	0.33	0.33
WORK RATE	HA/H	0.75	0.75	0.70	0.70	0.53
LATERAL DIRECTIONAL ANGLE	RAD.	0.62	0.62	0.62	0.62	0.62
SOIL SPECIFICATION						
WORKABILITY CRITERION	% FC	105	110	105	110	110
MOISTURE CONTENT	%W/W	30.08	31.51	30.08	31.51	31.51
CONE INDEX	KPA	858	820	858	820	820
SPECIFIC WEIGHT	KN/CM3	13.05	13.05	13.05	13.05	13.05
FIELD CAPACITY	MM	110.00	110.00	110.00	110.00	110.00
OPERATING CONDITIONS						
PROBABILITY LEVEL	%	90	100	90	100	100
TRAVEL SPEED	M/S	2.64	2.64	1.85	1.85	1.85
FINISHING WEEK NUMBER		48	46	49	47	50
NUMBER OF PENALTY WEEKS		6	4	7	5	8
COST OF OPERATION POUNDS STERLING						
PLOUGH PURCHASE PRICE		1023	1023	1420	1420	1023
TRACTOR PURCHASE PRICE		10857	10857	7743	7743	5898
PRESENT ANNUAL COST OF TRACTOR		691	691	524	524	516
PRESENT ANNUAL COST OF PLOUGH		468	468	499	499	468
FUEL COST		621	621	472	472	468
LABOUR COST		996	996	1067	1067	1423
TIMELINESS PENALTY		18676	8134	25566	12866	33535
TOTAL COST OF THE SYSTEM		21452	10910	28128	15428	36410

TABLE 7.37: FEASIBLE TRACTOR-IPLEMENT COMBINATIONS FOR A 300 HA FARM
OPERATION STARTING AT WEEK 41 AND EXPECTED TO FINISH AT WEEK 42
PLOUGH OPERATING AT 80 % FIELD EFFICIENCY

	UNIT	COMBINATION NUMBER 1	2	3	4
TRACTOR SPECIFICATION					
POWER	KW	91	91	64	64
WEIGHT	KN	32	32	32	32
TRACTIVE EFFICIENCY	%	72	71	72	71
THEORETICAL PULL	KN	34.4	34.4	34.4	34.4
ACTUAL PULL	KN	24.8	24.8	24.8	24.8
SLIP	%	10	11	10	11
TYRE SIZE		18.4-38	18.4-38	18.4-38	18.4-38
PLOUGH SPECIFICATION					
PLOUGH DRAUGHT	KN	17.7	17.1	20.2	19.5
NUMBER OF PLOUGH BODIES		3	3	4	4
DEPTH OF CUT	M	0.30	0.30	0.30	0.30
WIDTH OF CUT	M	0.33	0.33	0.33	0.33
WORK RATE	HA/H	0.75	0.75	0.70	0.70
LATERAL DIRECTIONAL ANGLE	RAD.	0.62	0.62	0.62	0.62
SOIL SPECIFICATION					
WORKABILITY CRITERION	% FC	105	110	105	110
MOISTURE CONTENT	%W/W	30.08	31.51	30.08	31.51
CONE INDEX	KPA	858	820	858	820
SPECIFIC WEIGHT	KN/CM3	13.05	13.05	13.05	13.05
FIELD CAPACITY	MM	110.00	110.00	110.00	110.00
OPERATING CONDITIONS					
PROBABILITY LEVEL	%	90	100	100	100
TRAVEL SPEED	M/S	2.64	2.64	1.85	1.85
FINISHING WEEK NUMBER		49	47	50	48
NUMBER OF PENALTY WEEKS		7	5	8	6
COST OF OPERATION	POUNDS STERLING				
PLOUGH PURCHASE PRICE		1023	1023	1420	1420
TRACTOR PURCHASE PRICE		10857	10857	7743	7743
PRESENT ANNUAL COST OF TRACTOR		691	691	524	524
PRESENT ANNUAL COST OF PLOUGH		468	468	499	499
FUEL COST		621	621	472	472
LABOUR COST		996	996	1067	1067
TIMELINESS PENALTY		25566	12866	33535	18676
TOTAL COST OF THE SYSTEM		28342	15642	36097	21238

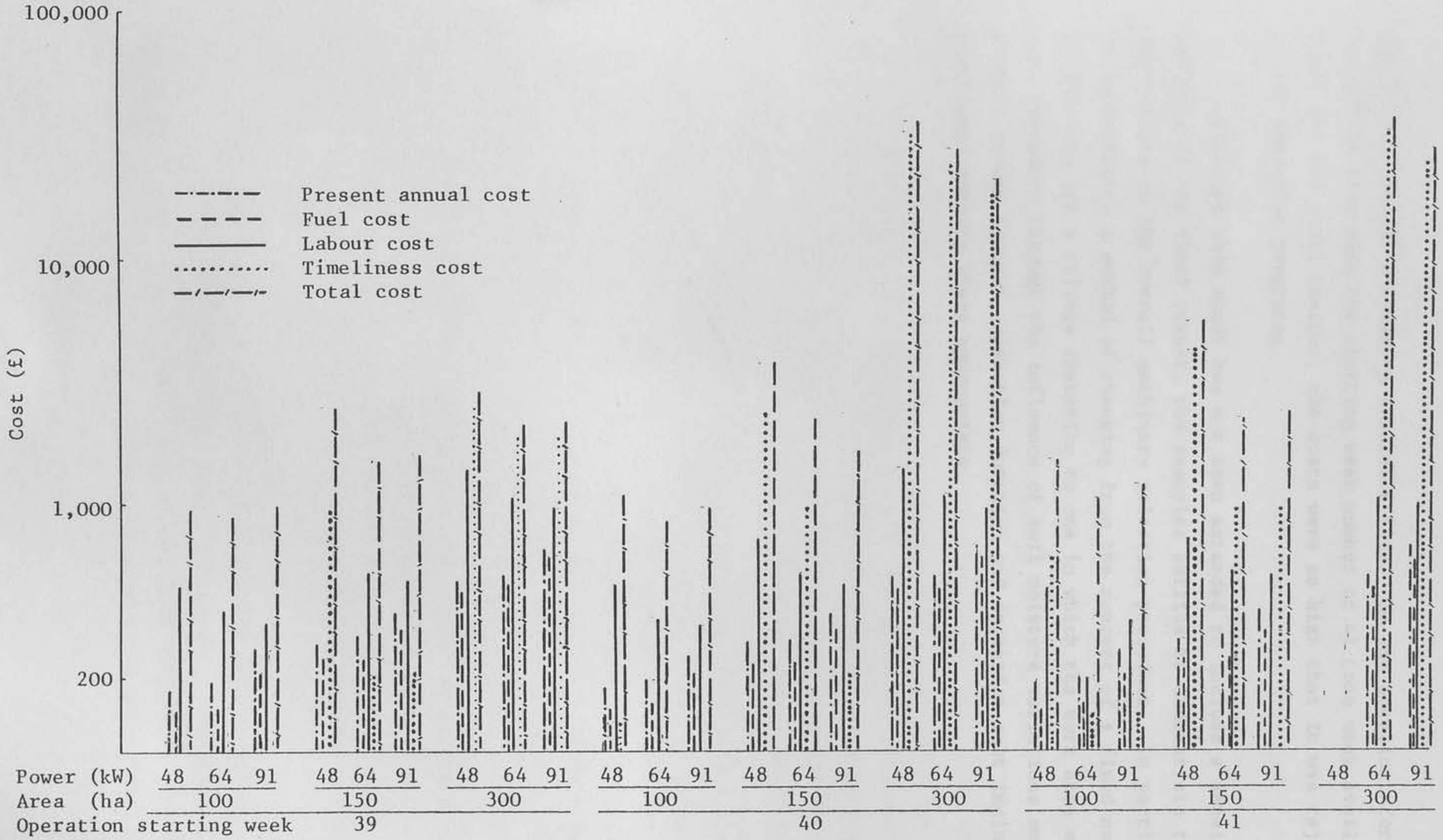

FIG. 7.34: Plough costs related to farm size, tractor size and time span, at 105% soil workability criterion

the total cost for decreasing available time. On one occasion, for the 300 ha farm with the starting week number of 41 (one week available time) and the small tractor, the costs were so high that it was rejected by the selection programme.

Although this study has not been extended to include a sensitively analysis of the final result, the examples suffice to demonstrate the feasibility of the overall machinery selection procedure. In particular, it demonstrates a method of changing from the concept of a fixed number of workdays for a tillage operation to one in which the work days are cost dependent through the influence of soil moisture variations on tractor plough draught, operation duration and operation cost including timeliness penalty where appropriate.

8. PROSPECTIVE IMPROVEMENTS AND APPLICATIONS

8.1 The soil moisture prediction model is designed to predict the variations of soil moisture content at a given depth. The present version of the model considers only two types of soil surface cover namely, grass and bare soil. There is information available in the literature which could be utilised in order to predict soil moisture fluctuations under a greater range of soil surface covers. The model can be used for the estimation of irrigation requirements as well as being a useful tool in land drainage design projects.

A major limitation of the model in the present version is the assumption of a homogeneous soil throughout the profile. Although this simplification was acceptable for the development of the model, the drainage procedure can be readily amended to account for varying soil pressure head with depth. This alteration would make the model applicable to layered soils and to soils with a low ground water table.

8.2 The workday probability prediction model is flexible and already contains a considerable variety of output options, simply by using different input data. This model is used to predict available days for other soil engaging operations. By imposing other restrictions such as rainfall and wind intensity and durations, the procedure can be adopted to predict available days for spraying and haymaking operations.

8.3 The prime objective of developing the tractor selection programme is to provide a tool for a farmer, farm manager, and mechanisation advisers so that he can select the tractor fleet which will enable him to complete operations of his farm(s) conveniently, satisfactorily, economically and timeously.

The present version of this programme while demonstrating the feasibility of the approach, falls short of this objective because it is designed for a single operation, a single crop and single tractor. It requires extension and improvement to evaluate the selection of a tractor fleet for whole farm operations with multiple cropping enterprises and to include refinements for error trapping. Procedures and techniques are available to carry out these improvements and data can be obtained from other studies to test the final form of the programme.

The developed version of this programme, combined with other programmes mentioned earlier, can be used to compile a guide on the national work days available for farm operations (probabilistic), on tractor selection and on proper use of existing machinery with particular emphasis on balancing timeliness penalties against power demand for fuel conservation.

9. CONCLUSIONS

9.1 The daily fluctuations of soil moisture content and the frequency of occurrence of a given soil moisture level can be predicted using simple soil and weather data.

9.2 Cone index is strongly correlated to soil moisture content and bulk density and can be predicted from these properties with a high level of accuracy.

9.3 Cone indices are a satisfactory measure of soil strength in the prediction of both tractor performance and plough draught.

9.4 The average cone indices at median depth of a segment are more accurate measures of soil strength than the average for all the depth of the segment.

9.5 Plough draught is characterised by soil cone index; bulk density; moisture content, depth and width of cut, plough tail angle and ploughing speed.

9.6 The selection of a unique level of soil moisture content to define soil workability criterion has no practical significance. The optimisation of soil moisture content for a given tractor/plough/terrain combination in order to identify the suitable soil moisture content level for ploughing is both more practical and a major advance on existing procedures.

9.7 For a given set of economic and engineering constraints, available days for soil tillage can be calculated and predicted.

9.8 The use of a constant drying rate (drainage coefficient) for a soil was found to be unrealistic and the rate of soil drying was related to soil moisture content.

9.9 Characterising the soil drying curves by means of the hydraulic conductivities and soil moisture contents at field capacity and at saturation has greater practical significance than the use of regression coefficients.

9.10 This study demonstrates the feasibility of a comprehensive computer model for the selection of economically viable tractor plough combinations by predicting traction, plough draught and available work days for a given climate and soil type within a machinery, labour and timeliness penalty cost framework.

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detected on 27 and 28th July for the former case and 18th July for the latter occasion when CEL 2 recorded 12.1 cm Hg. while CEL 1 and CEL 3 showed 34 and 40.4, respectively.

Another major discrepancy between measured and predicted soil moisture contents occurred towards the end of August and beginning of September, where after a fairly dry period and despite the fall of around 50 mm of rainfall, there was hardly any response on the measured values while the predicted values showed an appropriate rise in response to the rainfall. This could be attributed in the grass plot partly to interception by the vegetation and evaporating some of the rainfall before it reaches the soil and partly to the lateral drainage which may occur and then discharge the rainfall from the soil before it can reach to a level at which the tensiometer pot is installed. The excellent agreement between measured and predicted soil moisture content for the rest of the year in both soils under grass and bare soil, its constant response to rainfall and to drying in these periods, and its very simple data requirement justifies its use for prediction of soil moisture content for winter, spring and autumn seasons, i.e. the most critical season for ploughing and cultivation. The model can be tested for very dry seasons if a more reliable technique such as Neutron scattering method is available. Tensiometers were used in this study due to their simplicity and availability in order to obtain a trend in the fluctuation of soil moisture content. The drainage component of the model was tested separately and is described in the coming section.

7.2 Test of the Drainage Component of the Soil Moisture Model

The results obtained from the drainage experiment, 5.5, were plotted and the best curve was fitted for each soil (Figures 7.7 and 7.8). The following general equation was found to yield the best predicted results:

$$M = \frac{C_1}{DAY} + C_2 \qquad 7.3$$

where: M is the soil moisture content at the end of the day,

DAY is the day number for which soil moisture content is being calculated and,

C_1 and C_2 are constants which depend on type and moisture characteristics of the soil.

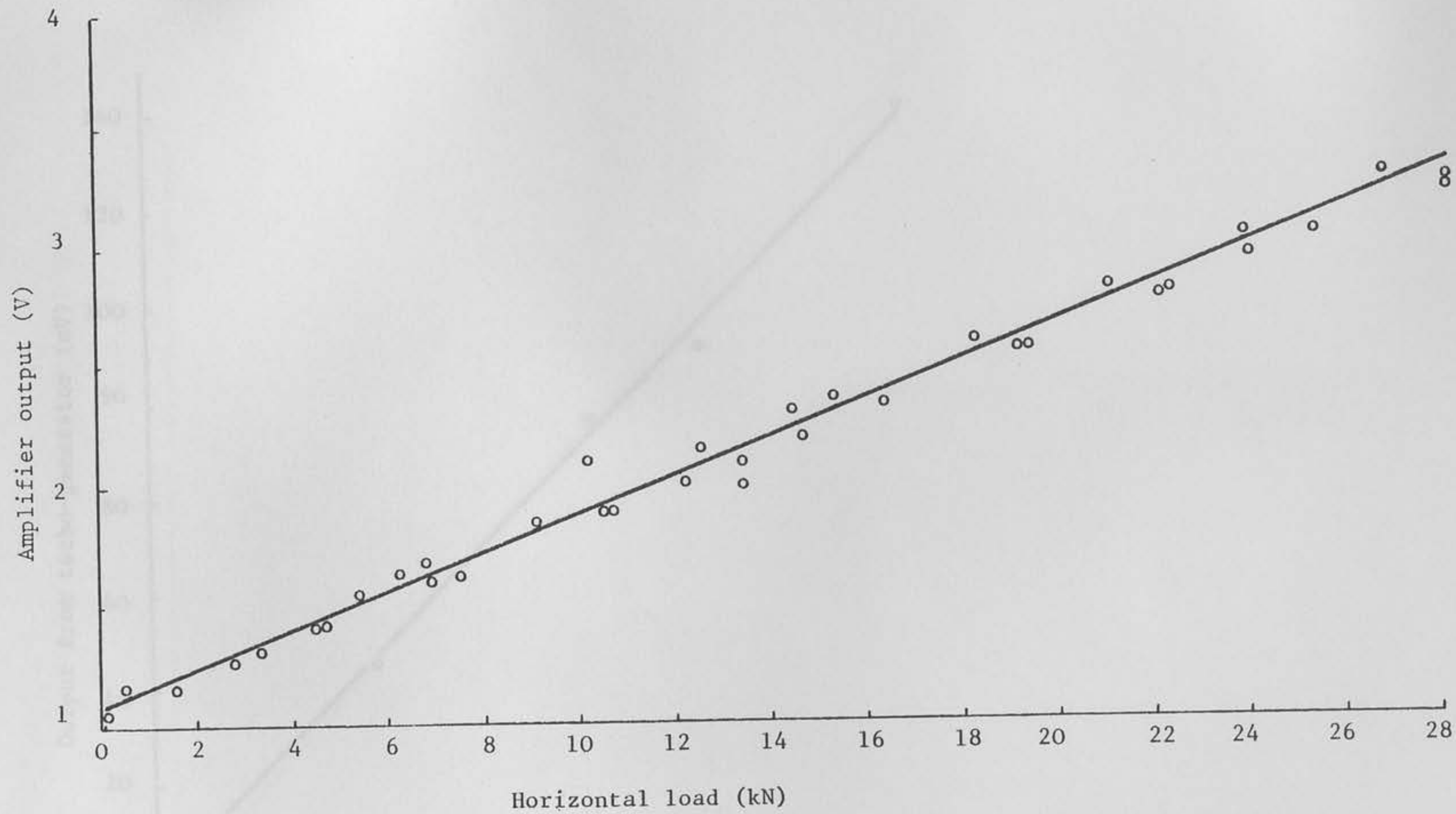
11:

APPENDICES

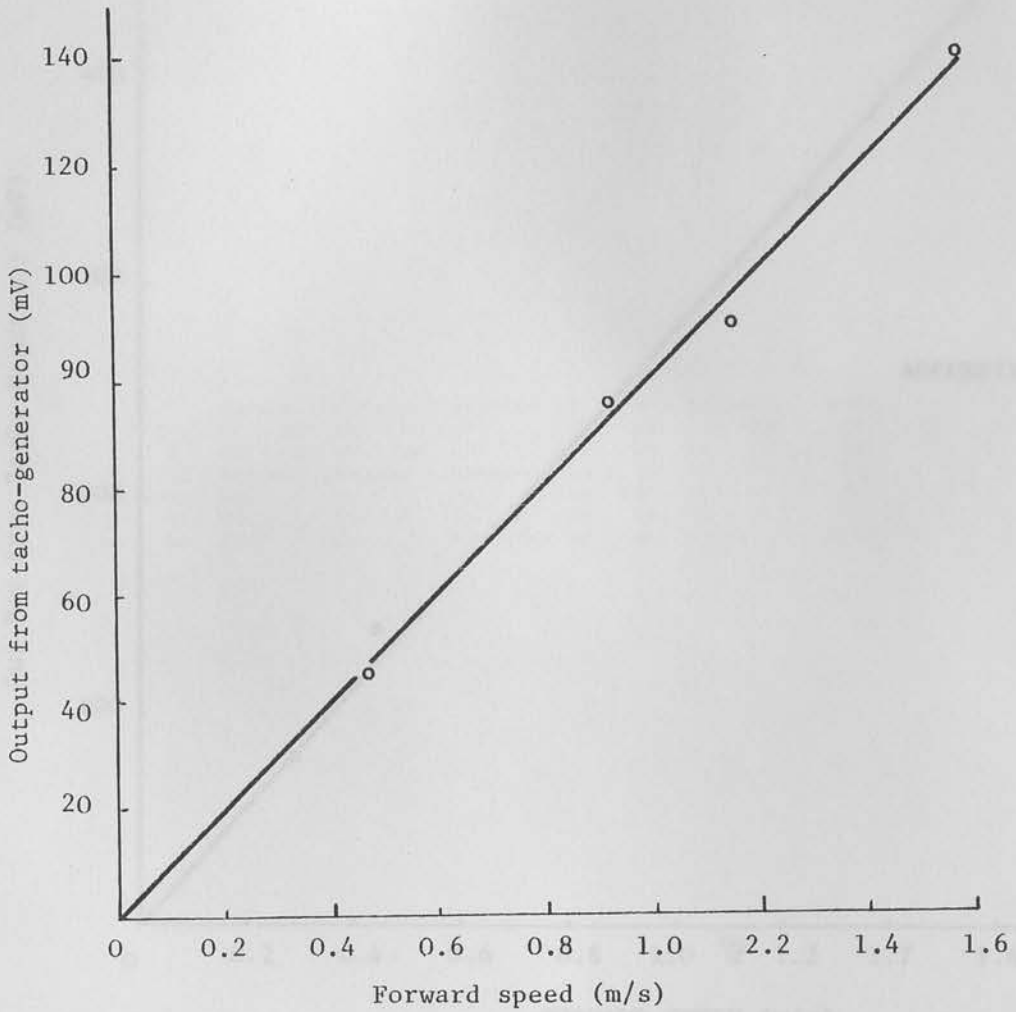
APPENDIX A

CALIBRATION

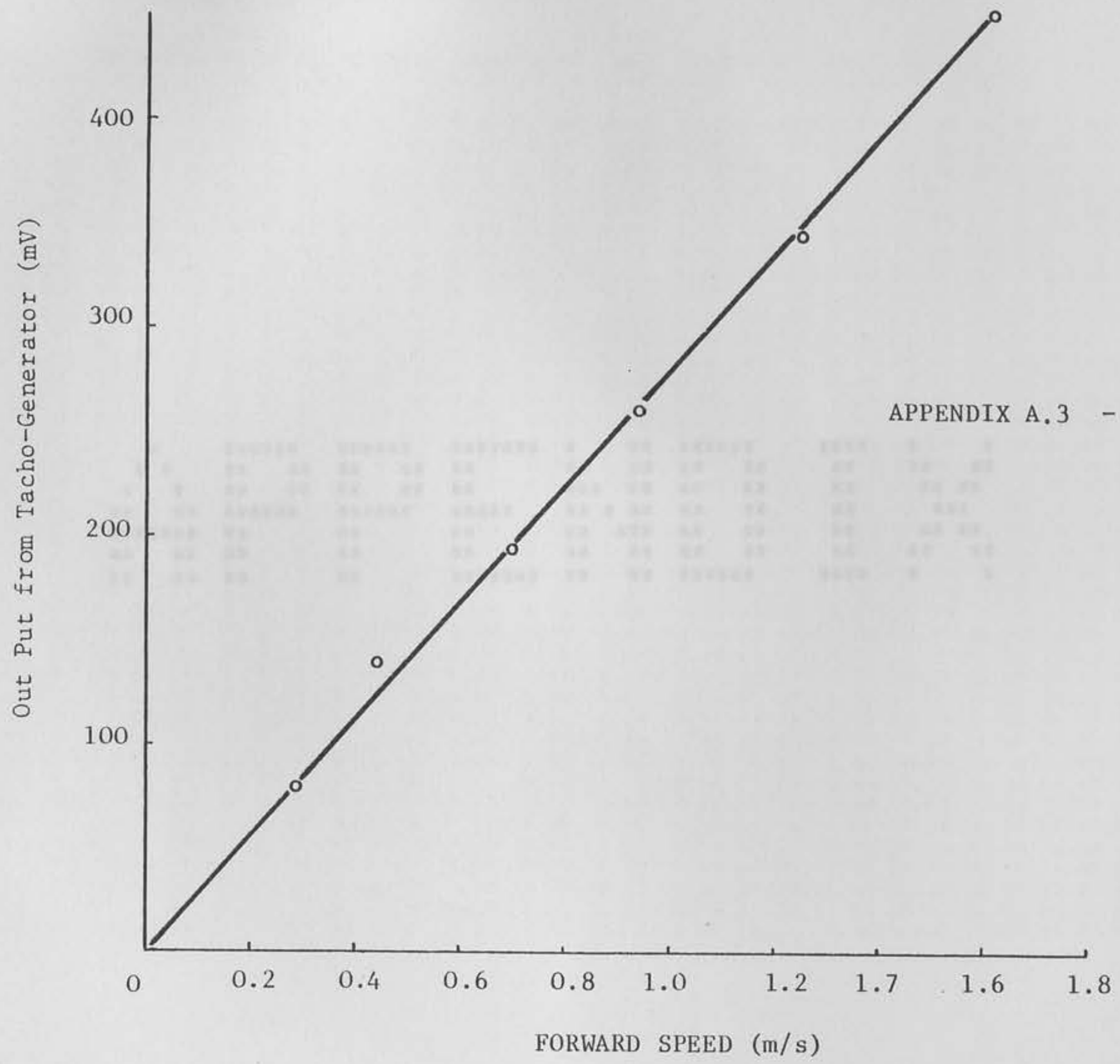
FIGURES



APPENDIX A.1; Calibration figures for Scholz dynamometer horizontal load.



APPENDIX A.2: Calibration figures for the tacho-generator on tractor wheel



APPENDIX A.3 - Calibration figures for the tacho-generator on the fifth wheel.

APPENDIX B

APPENDIX B.1

RESULTS OF THE PLOUGH DRAUGHT EXPERIMENT

DEFINITIONS OF THE HEADINGS HAVE BEEN GIVEN IN SECTION 5

REP	DATE	RN	FNA	R1	FN	DY	PL	SD	R2	SP	HORZ	VERT	WS	WS2	SLIP	BD	MC	CI1	CI2	PL2	CI3	CI4
1	12 12 79	1	S7	1	1	1	1	1	1	S	2.56	11.52	0.63	0.56	10.57	1.51	26.26	20.30	23.70	0.90	446.60	521.40
2	12 12 79	2	S7	1	1	1	1	1	1	M	3.36	10.64	1.14	0.98	13.78	1.51	26.26	20.30	23.70	0.90	446.60	521.40
3	12 12 79	3	S7	1	1	1	1	1	1	F	3.55	11.46	1.68	1.37	18.60	1.51	26.26	20.30	23.70	0.90	446.60	521.40
4	12 12 79	7	FC	3	2	1	1	1	1	S	5.12	10.07	0.55	0.31	44.06	1.43	30.17	22.30	18.90	0.90	490.60	415.80
5	12 12 79	8	FC	3	2	1	1	1	1	M	3.92	10.42	1.09	0.73	32.88	1.43	30.17	22.30	18.90	0.90	490.60	415.80
6	12 12 79	9	FC	3	2	1	1	1	1	F	4.16	10.29	1.62	1.21	25.43	1.43	30.17	22.30	18.90	0.90	490.60	415.80
7	12 12 79	13	LF	5	3	1	1	1	1	S	3.89	10.33	0.79	0.66	16.62	1.54	24.06	23.20	21.10	0.90	510.40	464.20
8	12 12 79	14	LF	5	3	1	1	1	1	M	5.62	9.31	1.36	1.08	20.80	1.54	24.06	23.20	21.10	0.90	510.40	464.20
9	12 12 79	15	LF	5	3	1	1	1	1	F	5.80	9.57	1.58	1.25	20.71	1.54	24.06	23.20	21.10	0.90	510.40	464.20
10	12 12 79	22	S7	8	1	1	2	0	2	S	3.22	4.06	0.61	0.47	22.28	1.51	26.26	20.30	23.70	0.62	446.60	521.40
11	12 12 79	23	S7	8	1	1	2	0	2	M	3.61	1.57	1.04	0.89	13.98	1.51	26.26	20.30	23.70	0.62	446.60	521.40
12	12 12 79	24	S7	8	1	1	2	0	2	F	4.99	3.51	1.58	1.22	22.74	1.51	26.26	20.30	23.70	0.62	446.60	521.40
13	13 12 79	31	FC	11	2	1	2	0	3	S	3.15	7.97	0.64	0.53	17.33	1.44	30.17	22.30	18.90	0.62	490.60	415.80
14	13 12 79	32	FC	11	2	1	2	0	3	M	3.15	8.37	1.11	0.92	16.87	1.44	30.17	22.30	18.90	0.62	490.60	415.80
15	13 12 79	33	FC	11	2	1	2	0	3	F	3.98	8.62	1.60	1.32	17.29	1.44	30.17	22.30	18.90	0.62	490.60	415.80
16	13 12 79	34	LF	12	3	1	2	0	1	S	3.19	8.32	0.62	0.51	17.61	1.54	24.06	23.20	21.10	0.62	510.40	464.20
17	13 12 79	35	LF	12	3	1	2	0	1	M	3.98	8.57	1.11	0.92	17.36	1.54	24.06	23.20	21.10	0.62	510.40	464.20
18	13 12 79	36	LF	12	3	1	2	0	1	F	3.97	9.04	1.71	1.44	15.50	1.54	24.06	23.20	21.10	0.62	510.40	464.20
19	13 12 79	40	SH	14	4	1	2	0	1	S	4.44	7.73	0.64	0.49	24.26	1.51	24.75	5.70	4.10	0.62	125.40	90.20
20	13 12 79	41	SH	14	4	1	2	0	1	M	4.35	8.26	1.06	0.85	20.03	1.51	24.75	5.70	4.10	0.62	125.40	90.20
21	13 12 79	42	SH	14	4	1	2	0	1	F	5.45	8.24	1.57	1.19	24.36	1.51	24.75	5.70	4.10	0.62	125.40	90.20
22	13 12 79	49	SH	17	4	1	1	1	1	S	6.95	4.66	0.80	0.39	50.98	1.51	24.75	5.70	4.10	0.90	125.40	90.20
23	13 12 79	50	SH	17	4	1	1	1	1	M	6.77	5.48	1.15	0.64	44.08	1.51	24.75	5.70	4.10	0.90	125.40	90.20
24	13 12 79	51	SH	17	4	1	1	1	1	F	6.89	5.76	1.69	1.04	38.29	1.51	24.75	5.70	4.10	0.90	125.40	90.20
25	18 12 79	52	LF	18	3	2	1	1	1	S	3.44	6.74	0.66	0.56	14.95	1.54	24.27	21.00	18.80	0.90	462.00	413.60
26	18 12 79	53	LF	18	3	2	1	1	1	M	4.86	6.46	1.12	0.92	18.07	1.54	24.27	21.00	18.80	0.90	462.00	413.60
27	18 12 79	54	LF	18	3	2	1	1	1	F	6.16	6.94	2.04	1.62	20.61	1.54	24.27	21.00	18.80	0.90	462.00	413.60
28	18 12 79	58	LF	20	3	2	1	0	1	S	3.41	6.68	0.67	0.54	19.44	1.54	24.27	21.00	18.80	0.90	462.00	413.60
29	18 12 79	59	LF	20	3	2	1	0	1	M	4.10	6.67	1.14	0.91	19.74	1.54	24.27	21.00	18.80	0.90	462.00	413.60
30	18 12 79	60	LF	20	3	2	1	0	1	F	5.63	6.55	1.86	1.43	23.36	1.54	24.27	21.00	18.80	0.90	462.00	413.60
31	18 12 79	64	FC	22	2	2	1	0	1	S	4.41	7.07	0.66	0.50	24.09	1.44	28.76	16.20	16.00	0.90	356.40	352.00
32	18 12 79	65	FC	22	2	2	1	0	1	M	5.77	8.23	1.12	0.86	23.38	1.44	28.76	16.20	16.00	0.90	356.40	352.00
33	18 12 79	66	FC	22	2	2	1	0	1	F	5.10	7.73	2.07	0.99	52.26	1.44	28.76	16.20	16.00	0.90	356.40	352.00
34	18 12 79	70	FC	24	2	2	2	0	1	S	1.72	9.94	0.60	0.50	15.76	1.44	28.76	16.20	16.00	0.62	356.40	352.00
35	18 12 79	71	FC	24	2	2	2	0	1	M	2.32	8.55	1.09	0.92	16.27	1.44	28.76	16.20	16.00	0.62	356.40	352.00
36	18 12 79	72	FC	24	2	2	2	0	1	F	3.46	8.32	1.99	1.62	18.80	1.44	28.76	16.20	16.00	0.62	356.40	352.00
37	18 12 79	76	LF	26	3	2	2	0	1	S	2.22	6.73	0.72	0.61	14.68	1.54	24.27	21.00	18.80	0.62	462.00	413.60
38	18 12 79	77	LF	26	3	2	2	0	1	M	2.84	5.99	1.12	0.96	14.28	1.54	24.27	21.00	18.80	0.62	462.00	413.60
39	18 12 79	78	LF	26	3	2	2	0	1	F	3.21	6.40	2.14	1.82	15.11	1.54	24.27	21.00	18.80	0.62	462.00	413.60

APPENDIX B.1 CONTINUED

REF	DATE	RN	FNA	R1	FN	DY	PL	SD	R2	SF	HORZ	VERT	WS	WS2	SLIP	BD	MC	CI1	CI2	FL2	CI3	CI4
40	14 1 80	82	LF	30	3	3	2	1	1	S	3.33	3.85	0.69	0.59	14.29	1.54	25.97	33.90	38.30	0.62	745.80	842.60
41	14 1 80	83	LF	30	3	3	2	1	1	M	4.76	4.61	1.50	1.16	22.39	1.54	25.97	33.90	38.30	0.62	745.80	842.60
42	14 1 80	84	LF	30	3	3	2	1	1	F	4.63	5.20	2.20	1.76	20.07	1.54	25.97	33.90	38.30	0.62	745.80	842.60
43	14 1 80	88	FC	32	2	3	2	1	1	S	4.68	4.70	0.85	0.61	28.21	1.44	22.76	30.10	28.40	0.62	662.20	624.80
44	14 1 80	89	FC	32	2	3	2	1	1	M	4.23	4.60	1.45	1.10	24.10	1.44	22.76	30.10	28.40	0.62	662.20	624.80
45	14 1 80	90	FC	32	2	3	2	1	1	F	5.78	5.15	2.08	1.51	27.35	1.44	22.76	30.10	28.40	0.62	662.20	624.80
46	14 1 80	94	SH	34	4	2	2	1	1	S	4.11	4.31	0.89	0.64	28.51	1.51	22.93	17.30	15.70	0.62	380.60	345.40
47	14 1 80	95	SH	34	4	2	2	1	1	M	4.48	4.48	1.47	1.05	28.50	1.51	22.93	17.30	15.70	0.62	380.60	345.40
48	14 1 80	96	SH	34	4	2	2	1	1	F	5.12	4.91	2.09	1.50	27.96	1.51	22.93	17.30	15.70	0.62	380.60	345.40
49	14 1 80	100	FC	36	2	3	1	1	1	S	3.91	6.07	0.80	0.31	60.43	1.44	22.76	30.10	28.40	0.90	662.20	624.80
50	14 1 80	101	FC	36	2	3	1	1	1	M	6.65	6.72	1.30	0.66	48.84	1.44	22.76	30.10	28.40	0.90	662.20	624.80
51	14 1 80	102	FC	36	2	3	1	1	1	F	7.09	6.88	2.01	1.21	39.88	1.44	22.76	30.10	28.40	0.90	662.20	624.80
52	14 1 80	106	LF	38	3	3	1	1	1	S	4.49	5.82	0.82	0.40	51.62	1.54	25.97	33.90	38.30	0.90	745.80	842.60
53	14 1 80	107	LF	38	3	3	1	1	1	M	4.77	5.98	1.43	0.86	39.83	1.54	25.97	33.90	38.30	0.90	745.80	842.60
54	14 1 80	108	LF	38	3	3	1	1	1	F	5.58	6.33	2.05	1.32	35.74	1.54	25.97	33.90	38.30	0.90	745.80	842.60
55	14 1 80	114	SH	41	4	2	1	1	2	S	5.86	6.46	0.83	0.42	48.71	1.51	22.93	17.30	15.70	0.90	380.60	345.40
56	14 1 80	115	SH	41	4	2	1	1	2	M	6.05	6.20	1.42	0.84	40.79	1.51	22.93	17.30	15.70	0.90	380.60	345.40
57	14 1 80	116	SH	41	4	2	1	1	2	F	6.95	6.13	2.00	1.23	38.65	1.51	22.93	17.30	15.70	0.90	380.60	345.40
58	14 1 80	120	S7	44	1	2	1	1	1	S	2.36	6.31	0.82	0.50	39.18	1.51	24.81	16.20	13.00	0.90	356.40	286.00
59	14 1 80	121	S7	44	1	2	1	1	1	M	4.04	5.89	1.45	1.00	30.91	1.51	24.81	16.20	13.00	0.90	356.40	286.00
60	14 1 80	122	S7	44	1	2	1	1	1	F	4.63	6.35	2.08	1.44	30.74	1.51	24.81	16.20	13.00	0.90	356.40	286.00
61	14 1 80	126	S7	46	1	2	2	1	1	S	3.38	5.42	0.81	0.77	5.04	1.51	24.81	16.20	13.00	0.62	356.40	286.00
62	14 1 80	127	S7	46	1	2	2	1	1	M	3.30	5.69	1.44	1.25	12.89	1.51	24.81	16.20	13.00	0.62	356.40	286.00
63	14 1 80	129	S7	47	1	2	2	1	2	F	3.95	5.71	2.09	0.15	93.02	1.51	24.81	16.20	13.00	0.62	356.40	286.00
64	15 1 80	132	HM	60	5	1	1	1	1	S	5.35	6.06	0.83	0.34	58.52	1.29	31.82	22.50	19.00	0.90	495.00	418.00
65	15 1 80	133	HM	60	5	1	1	1	1	M	4.84	6.29	1.43	0.82	42.89	1.29	31.82	22.50	19.00	0.90	495.00	418.00
66	15 1 80	134	HM	60	5	1	1	1	1	F	5.23	7.00	2.17	1.68	22.51	1.29	31.82	22.50	19.00	0.90	495.00	418.00
67	15 1 80	138	HM	62	5	1	2	1	1	S	3.44	3.50	0.77	0.79	-2.69	1.29	31.82	22.50	19.00	0.62	495.00	418.00
68	15 1 80	139	HM	62	5	1	2	1	1	M	3.57	4.67	1.36	1.24	8.93	1.29	31.82	22.50	19.00	0.62	495.00	418.00
69	15 1 80	140	HM	62	5	1	2	1	1	F	5.43	5.40	1.97	1.46	26.06	1.29	31.82	22.50	19.00	0.62	495.00	418.00

APPENDIX B.1 CONTINUED

REF	DATE	RN	FNA	R1	FN	DY	PL	SD	R2	SP	HORZ	VERT	WS	WS2	SLIP	BD	MC	CI1	CI2	PL2	CI3	CI4
70	16 1 80	144	S7	64	1	3	2	1	1	S	3.07	3.33	0.78	0.61	21.91	1.51	25.99	17.90	15.70	0.62	393.80	345.40
71	16 1 80	145	S7	64	1	3	2	1	1	M	4.14	3.65	1.39	1.01	27.34	1.51	25.99	17.90	15.70	0.62	393.80	345.40
72	16 1 80	146	S7	64	1	3	2	1	1	F	4.86	3.24	2.07	1.54	25.80	1.51	25.99	17.90	15.70	0.62	393.80	345.40
73	16 1 80	150	FC	67	2	4	2	1	1	S	2.90	2.72	0.79	0.71	9.53	1.44	21.90	20.80	13.70	0.62	457.60	301.40
74	16 1 80	151	FC	67	2	4	2	1	1	M	1.62	2.48	1.41	1.13	19.51	1.44	21.90	20.80	13.70	0.62	457.60	301.40
75	16 1 80	152	FC	67	2	4	2	1	1	F	2.56	2.40	2.03	1.67	17.74	1.44	21.90	20.80	13.70	0.62	457.60	301.40
76	16 1 80	156	LF	69	3	4	2	1	1	S	3.68	3.01	0.82	0.60	26.71	1.54	26.53	23.10	20.10	0.62	508.20	442.20
77	16 1 80	157	LF	69	3	4	2	1	1	M	3.43	3.03	1.37	1.05	22.84	1.54	26.53	23.10	20.10	0.62	508.20	442.20
78	16 1 80	158	LF	69	3	4	2	1	1	F	3.27	2.90	2.03	1.55	23.59	1.54	26.53	23.10	20.10	0.62	508.20	442.20
79	16 1 80	162	SH	71	4	3	2	1	1	S	3.68	2.43	0.61	0.42	32.05	1.51	23.12	18.80	11.30	0.62	413.60	248.60
80	16 1 80	163	SH	71	4	3	2	1	1	M	4.55	2.72	1.35	0.99	26.79	1.51	23.12	18.80	11.30	0.62	413.60	248.60
81	16 1 80	164	SH	71	4	3	2	1	1	F	5.23	3.24	1.96	1.43	26.82	1.51	23.12	18.80	11.30	0.62	413.60	248.60
82	16 1 80	168	SH	73	4	3	1	1	1	S	4.34	3.54	0.58	0.20	65.30	1.51	23.12	18.80	11.30	0.90	413.60	248.60
83	16 1 80	169	SH	73	4	3	1	1	1	M	4.99	3.80	1.35	0.74	44.86	1.51	23.12	18.80	11.30	0.90	413.60	248.60
84	16 1 80	170	SH	73	4	3	1	1	1	F	5.88	3.65	1.92	1.18	38.69	1.51	23.12	18.80	11.30	0.90	413.60	248.60
85	16 1 80	174	LF	75	3	4	1	1	1	S	3.96	3.66	0.59	0.40	33.37	1.54	26.53	23.10	20.10	0.90	508.20	442.20
86	16 1 80	175	LF	75	3	4	1	1	1	M	4.74	4.06	1.37	0.97	29.15	1.54	26.53	23.10	20.10	0.90	508.20	442.20
87	16 1 80	176	LF	75	3	4	1	1	1	F	5.61	4.45	1.99	1.41	29.13	1.54	26.53	23.10	20.10	0.90	508.20	442.20
88	16 1 80	180	FC	77	2	4	1	1	1	S	3.66	4.12	0.59	0.38	35.11	1.44	21.90	20.80	13.70	0.90	457.60	301.40
89	16 1 80	181	FC	77	2	4	1	1	1	M	4.25	4.08	1.37	0.95	30.08	1.44	21.90	20.80	13.70	0.90	457.60	301.40
90	16 1 80	182	FC	77	2	4	1	1	1	F	6.22	4.99	1.94	1.42	27.06	1.44	21.90	20.80	13.70	0.90	457.60	301.40
91	16 1 80	186	S7	79	1	3	1	1	1	S	4.60	3.80	0.58	0.38	34.79	1.51	25.99	17.90	15.70	0.90	393.80	345.40
92	16 1 80	187	S7	79	1	3	1	1	1	M	4.47	3.86	1.31	1.01	22.98	1.51	25.99	17.90	15.70	0.90	393.80	345.40
93	16 1 80	188	S7	79	1	3	1	1	1	F	6.38	4.35	1.66	1.07	35.35	1.51	25.99	17.90	15.70	0.90	393.80	345.40
94	18 1 80	192	HM	85	5	2	1	1	1	S	4.10	12.31	0.75	0.54	28.09	1.29	30.12	21.80	17.00	0.90	479.60	374.00
95	18 1 80	193	HM	85	5	2	1	1	1	M	4.57	13.12	1.39	1.06	24.07	1.29	30.12	21.80	17.00	0.90	479.60	374.00
96	18 1 80	194	HM	85	5	2	1	1	1	F	5.17	13.74	2.02	1.54	23.54	1.29	30.12	21.80	17.00	0.90	479.60	374.00
97	18 1 80	198	HM	87	5	2	2	1	1	S	5.64	9.10	0.78	0.59	25.10	1.29	30.12	21.80	17.00	0.62	479.60	374.00
98	18 1 80	199	HM	87	5	2	2	1	1	M	4.24	9.74	1.36	1.09	20.08	1.29	30.12	21.80	17.00	0.62	479.60	374.00
99	18 1 80	200	HM	87	5	2	2	1	1	F	7.45	10.81	1.42	1.10	22.31	1.29	30.12	21.80	17.00	0.62	479.60	374.00
100	24 1 80	204	HM	95	5	3	2	1	1	S	2.26	8.92	0.73	0.57	21.72	1.29	32.70	30.20	28.10	0.62	664.40	618.20
101	24 1 80	205	HM	95	5	3	2	1	1	M	3.32	8.39	1.33	0.91	31.54	1.29	32.70	30.20	28.10	0.62	664.40	618.20
102	24 1 80	206	HM	95	5	3	2	1	1	F	3.06	9.17	1.91	1.52	20.48	1.29	32.70	30.20	28.10	0.62	664.40	618.20
103	24 1 80	210	HM	97	5	3	1	1	1	S	3.73	5.02	0.81	0.59	27.19	1.29	32.70	30.20	28.10	0.90	664.40	618.20
104	24 1 80	211	HM	97	5	3	1	1	1	M	4.25	5.39	1.42	1.08	24.14	1.29	32.70	30.20	28.10	0.90	664.40	618.20
105	24 1 80	212	HM	97	5	3	1	1	1	F	4.81	5.81	2.12	1.64	22.54	1.29	32.70	30.20	28.10	0.90	664.40	618.20

APPENDIX C

TENSION RESULTS

APPENDIX C.1 TENSION DATA FOR MACMERRY SOIL YEAR 1978

	G R A S S							B A R E S O I L						
	DEPTH 200 MM			DEPTH 400 MM				DEPTH 200 MM			DEPTH 400 MM			
DATE	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H
MARCH														
6	9.9	10.9	11.0	8.7	9.9	9.8	49.0	11.6	9.5	12.4	11.2	10.5	10.6	53.0
13	10.8	10.9	10.7	7.8	8.7	8.6	49.0	9.0	8.4	12.2	9.0	8.9	9.0	53.0
15	10.4	10.4	10.3	7.8	9.0	8.9	49.0	10.0	8.1	11.8	9.0	9.1	9.9	53.0
20	9.9	10.0	10.0	7.3	8.5	8.4	49.0	9.9	9.4	11.4	8.9	8.7	9.0	53.0
21	10.5	10.5	10.4	7.8	9.2	9.1	48.0	10.5	10.4	11.5	9.4	9.4	9.6	54.0
28	10.0	10.3	10.2	6.6	8.8	8.7	50.0	10.4	9.2	11.2	8.7	8.8	9.1	52.0
29	10.0	10.1	9.8	6.0	8.5	8.4	49.0	10.0	9.0	11.5	8.5	8.6	8.7	52.0
30	10.0	10.3	10.2	6.8	8.8	8.9	48.0	9.8	10.0	11.2	8.8	8.8	9.0	53.0
31	10.4	10.8	10.7	6.7	9.2	9.3	48.0	11.0	10.5	12.3	10.3	9.8	10.0	53.0
APRIL														
3	10.7	10.7	10.4	7.2	8.6	8.4	49.0	11.0	11.1	11.8	8.6	8.6	8.8	52.0
4	10.5	10.5	10.4	7.9	9.1	9.0	48.0	11.0	11.0	11.9	9.0	9.0	9.4	52.0
6	10.9	10.9	10.7	8.7	9.9	9.9	49.0	11.6	11.2	11.8	9.8	10.0	10.0	53.0
7	10.6	10.8	10.8	8.2	10.0	10.0	49.0	11.1	11.2	12.5	11.3	10.9	11.0	53.0
10	11.2	12.1	11.4	8.3	10.5	10.4	49.0	11.4	11.3	16.4	12.5	12.5	12.4	51.0
11	11.0	11.4	8.9	8.4	11.9	10.8	49.0	11.4	11.0	13.6	12.1	12.4	12.5	51.0
12	10.9	11.4	9.0	8.0	11.0	10.8	49.0	11.4	11.4	13.0	11.9	12.0	12.2	51.0
13	11.6	11.6	9.2	7.8	11.3	11.4	49.0	12.0	11.8	13.5	11.8	12.0	12.0	51.0
14	11.3	12.3	9.0	7.8	8.2	8.8	49.0	10.3	12.0	13.5	8.0	9.3	9.0	52.0
15	11.2	11.7	8.8	8.2	9.3	9.3	49.0	11.7	12.0	14.0	10.5	10.3	10.5	52.0
16	11.3	11.3	9.3	9.8	9.8	10.1	48.0	11.7	11.6	12.6	10.2	10.5	10.6	52.0
17	11.4	11.4	9.0	7.2	10.3	10.9	48.0	12.1	11.5	12.4	11.1	11.3	11.2	52.0
18	11.2	11.2	9.2	6.5	10.2	10.8	48.0	11.8	11.4	12.5	10.8	10.9	11.0	52.0
19	11.0	11.0	8.9	6.5	10.6	10.8	48.0	11.4	11.4	12.5	11.4	12.0	11.8	52.0
21	11.3	11.3	8.9	6.5	11.5	12.5	49.0	11.8	11.5	12.4	12.3	12.7	12.7	51.0
22	11.5	11.6	9.0	6.8	11.8	12.8	49.0	12.0	11.8	12.3	12.2	12.8	12.8	51.0
23	11.6	11.6	8.5	6.3	12.5	13.8	49.0	12.2	11.6	12.4	12.4	13.0	13.0	51.0
24	11.8	11.9	8.8	6.8	12.6	13.9	49.0	12.5	11.8	12.6	12.7	13.2	13.1	51.0
25	12.2	11.8	8.8	13.9	12.9	14.0	48.0	11.9	11.8	12.9	12.9	13.7	13.5	51.0
26	12.0	11.8	8.5	14.5	13.3	14.5	48.0	12.1	11.8	13.0	12.8	13.0	13.5	52.0
27	10.5	12.0	9.0	13.4	8.0	8.0	49.0	12.5	12.2	2.3	7.5	8.0	8.0	53.0
28	9.8	10.4	9.5	6.8	8.1	8.0	49.0	9.3	10.8	10.9	8.0	8.3	8.4	53.0

APPENDIX C.1 TENSION DATA FOR MACMERRY SOIL YEAR 1978

	GRASS							BARE SOIL						
	DEPTH 200 MM			DEPTH 400 MM				DEPTH 200 MM			DEPTH 400 MM			
DATE	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H
MAY														
3	10.6	10.8	9.5	10.0	10.0	10.0	49.0	11.1	11.0	11.5	10.1	10.2	10.3	52.0
4	10.8	10.9	8.9	10.2	9.6	9.7	49.0	11.1	11.1	11.8	10.7	10.6	10.5	52.0
5	10.5	10.6	9.0	8.0	8.2	8.0	49.0	10.8	11.0	11.5	8.0	8.2	8.5	52.0
6	10.8	11.0	9.2	8.2	8.4	8.3	49.0	11.0	11.2	12.0	8.3	8.5	8.8	52.0
7	11.0	11.0	9.0	9.0	9.3	9.3	48.0	11.3	11.0	11.8	9.5	9.6	9.7	52.0
8	10.9	10.9	9.0	9.4	9.2	9.4	48.0	11.0	11.1	11.8	9.8	10.0	10.0	52.0
9	11.1	11.3	9.2	10.2	9.8	10.0	48.0	11.1	11.2	12.0	10.4	10.8	10.8	51.0
10	10.8	10.9	9.0	11.0	10.8	11.0	48.0	11.0	11.3	12.0	11.0	11.1	10.8	51.0
11	10.8	10.9	8.5	11.2	10.8	11.4	48.0	11.4	11.3	12.0	11.3	11.5	11.4	51.0
12	11.2	11.2	9.0	12.0	11.8	12.1	48.0	11.5	11.5	12.0	11.2	11.5	11.5	51.0
13	11.3	11.3	9.0	12.5	11.8	12.8	48.0	11.5	11.5	12.0	11.5	11.9	11.8	51.0
14	11.2	11.3	9.0	12.5	12.2	13.8	48.0	11.5	11.5	12.3	11.5	12.0	11.8	51.0
15	11.5	11.5	8.5	12.8	12.5	14.0	48.0	11.9	11.8	12.3	11.5	12.1	12.0	51.0
16	10.9	11.4	8.6	13.5	12.3	13.9	48.0	11.3	11.7	12.7	12.0	12.6	12.4	52.0
17	11.0	11.3	9.0	14.5	14.0	16.0	48.0	11.2	11.8	12.5	12.6	13.0	12.8	52.0
18	11.0	11.3	8.7	15.4	13.8	15.9	48.0	11.1	11.6	12.5	12.7	13.7	13.1	52.0
19	11.0	11.1	9.0	17.4	15.5	18.3	48.0	11.3	12.0	12.7	13.0	14.3	14.0	51.0
20	11.2	11.3	9.0	18.5	15.7	19.3	48.0	11.5	12.0	12.5	13.5	14.8	14.3	51.0
22	12.0	8.5	8.5	21.0	15.5	21.8	47.0	12.2	12.0	12.5	14.5	14.8	15.0	50.0
23	11.8	8.5	8.4	20.9	17.3	22.3	47.0	12.2	11.9	12.5	12.6	13.8	14.3	50.0
24	11.8	11.8	11.8	17.0	13.5	16.0	47.0	11.5	11.8	12.3	9.0	9.3	9.3	50.0
25	11.9	12.2	12.1	18.5	13.8	16.6	46.0	10.6	10.5	12.2	9.6	10.0	9.9	50.0
26	11.8	12.0	12.0	21.5	15.0	18.8	46.0	10.5	9.3	12.0	11.0	11.0	11.0	50.0
27	11.8	12.0	12.2	23.5	17.0	21.8	46.0	10.9	9.3	12.3	11.5	11.6	11.5	51.0
28	11.6	12.0	12.2	26.5	19.0	22.5	45.0	10.8	9.0	12.3	12.0	12.0	12.0	51.0
29	11.8	12.3	12.3	27.0	19.9	27.4	45.0	11.5	9.3	12.5	12.4	12.4	12.4	52.0
30	11.9	12.3	12.3	31.8	22.5	30.5	45.0	11.8	9.0	12.5	12.9	13.0	13.0	51.0
31	11.5	12.0	12.0	41.0	26.0	34.8	45.0	12.0	11.5	12.5	14.2	14.3	14.2	51.0

APPENDIX C.1 TENSION DATA FOR MACMERRY SOIL YEAR 1978

	GRASS							BARE SOIL						
	DEPTH 200 MM			DEPTH 400 MM				DEPTH 200 MM			DEPTH 400 MM			
DATE	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H
*****	****	****	****	****	****	****	****	****	****	****	****	****	****	****
JUNE														
1	11.9	12.0	12.0	43.6	29.0	38.0	43.0	12.5	11.7	12.8	14.4	14.5	14.7	50.0
2	11.2	12.0	12.0	51.5	32.3	42.2	40.0	11.8	11.7	12.5	15.5	15.7	15.6	49.0
3	11.4	12.0	12.0	58.0	37.3	44.5	40.0	11.8	11.7	12.5	16.0	16.2	16.0	49.0
4	11.6	12.4	12.4	61.0	40.7	43.8	39.0	10.5	11.8	12.5	16.3	16.5	16.6	49.0
5	12.3	12.8	12.6	64.8	46.1	43.6	38.0	12.0	11.8	12.7	17.0	16.8	17.5	49.0
6	12.4	12.9	12.9	66.1	50.2	43.0	38.0	12.6	11.9	12.8	17.9	18.0	18.4	49.0
7	12.8	12.9	12.8	67.5	53.0	42.8	38.0	12.8	12.0	13.0	18.5	18.8	19.0	49.0
9	14.4	14.2	14.0	67.3	58.2	0.0	43.0	11.8	12.0	13.2	20.0	20.5	21.0	49.0
10	15.6	15.6	14.8	0.0	60.5	0.0	43.0	10.0	12.0	13.0	20.5	20.2	2.1	49.0
11	20.1	17.5	15.3	0.0	63.2	0.0	43.0	10.1	12.2	13.0	21.1	21.3	21.7	48.0
12	21.0	18.5	15.6	0.0	64.3	0.0	43.0	10.0	12.1	13.0	21.9	22.0	22.5	48.0
13	23.8	19.8	16.2	33.8	65.2	52.0	42.0	10.0	12.3	13.2	12.5	12.4	22.9	50.0
14	28.5	23.5	27.0	46.5	50.0	62.5	42.0	9.0	12.0	13.0	23.2	23.3	23.5	50.0
15	31.0	24.9	18.0	50.9	0.0	65.3	45.0	9.2	12.4	13.3	23.9	24.0	24.5	48.0
16	33.0	25.8	19.5	53.8	0.0	0.0	49.0	9.5	12.5	13.5	24.4	24.4	25.3	48.0
19	48.6	23.3	26.2	0.0	59.9	0.0	47.0	9.3	12.7	13.6	26.1	25.8	25.7	48.0
20	29.3	22.7	29.0	60.8	62.5	52.6	40.0	9.0	12.9	13.9	26.7	25.6	25.9	52.0
21	28.2	23.0	33.5	68.1	64.0	62.7	38.0	9.0	12.9	14.0	27.6	27.4	27.3	52.0
22	30.5	25.2	11.3	23.9	33.0	15.3	50.0	9.5	11.0	11.8	9.0	9.0	9.0	54.0
26	32.0	20.7	12.6	25.8	28.8	16.0	50.0	9.5	10.5	11.6	9.4	9.4	9.4	54.0
27	32.2	20.9	14.0	30.0	30.6	22.2	49.0	11.7	11.1	11.6	10.4	10.3	10.2	54.0
28	32.2	21.1	14.8	30.0	32.1	25.8	44.0	11.8	11.4	11.7	10.6	10.5	10.5	52.0
29	32.3	21.5	26.0	30.3	34.1	29.0	44.0	11.9	11.8	11.9	10.9	10.8	10.8	52.0
30	32.3	22.0	26.7	31.6	36.0	32.7	42.0	12.2	11.9	12.1	11.2	11.0	11.0	52.0
JULY														
3	32.3	22.7	9.0	30.0	34.0	30.7	42.0	12.0	11.0	11.5	10.7	10.5	10.5	53.0
4	32.4	23.2	10.5	22.7	8.0	8.0	54.0	10.7	10.5	10.9	8.0	8.5	8.5	54.0
6	32.5	11.8	13.8	9.5	10.2	10.4	54.0	10.9	11.2	11.5	10.0	10.0	10.0	54.0
7	32.5	12.3	14.4	10.2	10.8	11.0	53.0	10.3	11.5	11.8	10.5	10.5	10.5	52.0
10	32.2	13.7	15.4	15.9	15.4	17.5	52.0	9.8	11.8	12.0	12.0	11.7	11.6	52.0
11	32.2	13.9	15.2	16.9	16.5	19.6	51.0	9.9	11.9	11.9	12.6	12.3	12.2	52.0
12	13.8	13.9	15.6	17.8	17.6	21.1	50.0	9.8	12.0	12.1	13.2	12.5	12.3	53.0
13	15.8	14.5	16.0	19.9	19.8	24.8	48.0	9.8	12.2	12.4	13.6	13.2	13.0	53.0
14	16.8	14.6	16.2	22.5	21.5	28.9	49.0	9.5	12.2	12.3	14.8	13.3	13.2	52.0
17	19.3	15.7	17.4	34.8	29.8	46.5	46.0	9.5	12.7	12.8	15.7	14.7	14.6	52.0
18	19.7	16.2	18.2	40.2	33.6	52.3	45.0	9.5	12.5	12.7	16.2	15.7	15.5	50.0
20	22.0	17.9	19.7	48.8	39.7	58.5	43.0	9.5	12.7	13.0	18.0	17.0	17.0	50.0
21	22.6	18.3	19.6	50.2	41.8	59.9	43.0	9.5	13.0	13.3	17.6	16.7	17.0	50.0
24	23.6	19.6	20.7	55.7	47.0	62.7	40.0	9.6	13.3	13.5	17.3	16.9	19.2	50.0
25	24.8	21.2	21.8	56.5	47.6	64.0	40.0	9.5	13.3	13.5	17.2	16.9	19.1	50.0
27	25.1	22.0	21.1	57.8	51.2	61.8	39.0	9.4	13.5	13.7	15.2	15.1	15.3	51.0
28	26.0	22.9	22.6	58.8	52.5	60.6	39.0	9.3	13.5	13.7	14.5	14.3	14.6	51.0

APPENDIX C.1 TENSION DATA FOR MACMERRY SOIL YEAR 1978

	GRASS							BARE SOIL						
	DEPTH 200 MM			DEPTH 400 MM				DEPTH 200 MM			DEPTH 400 MM			
DATE	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H
AUGUST														
2	30.0	27.0	24.9	60.5	55.7	0.0	45.0	9.5	13.8	14.0	14.8	14.8	15.0	53.0
3	30.2	26.9	24.5	50.3	46.0	9.8	45.0	9.5	14.0	14.0	8.5	9.7	9.0	53.0
25	25.3	35.2	22.9	10.5	50.8	12.6	45.0	9.7	11.0	12.1	11.1	11.0	11.0	53.0
29	23.5	39.4	35.9	14.7	52.2	21.9	45.0	9.4	10.0	12.8	13.0	12.8	12.6	54.0
SEPTEMBER														
7	21.5	31.0	25.5	8.5	52.3	8.5	50.0	9.5	10.5	12.4	9.0	9.4	9.4	54.0
8	21.5	30.8	25.3	9.5	19.7	10.0	50.0	9.5	11.0	12.5	9.8	9.8	9.8	54.0
15	13.5	25.9	17.2	9.2	10.2	9.5	53.0	9.2	9.7	11.7	9.5	9.7	9.8	53.0
19	12.2	23.8	15.5	11.5	14.4	12.9	53.0	9.9	9.7	12.4	11.9	11.4	11.4	53.0
25	9.2	10.0	13.0	13.8	13.5	13.4	53.0	12.3	20.0	15.0	15.0	19.8	18.8	52.0
29	11.8	19.0	11.0	8.9	9.2	9.2	53.0	11.3	10.8	11.4	8.9	9.1	9.1	58.0
OCTOBER														
2	10.3	10.8	10.7	9.6	9.8	9.7	53.0	10.0	11.2	11.2	9.6	9.8	9.8	53.0
4	10.0	12.0	12.2	10.8	10.7	10.6	52.0	10.8	11.3	11.3	10.1	10.5	10.4	53.0
5	10.8	11.5	11.4	10.4	10.9	10.8	53.0	10.0	11.8	11.8	10.6	10.6	10.6	53.0
6	10.8	11.5	11.5	11.2	12.0	11.5	53.0	10.0	12.0	12.0	11.0	11.0	11.0	55.0
9	11.0	12.2	12.0	12.3	13.5	13.2	52.0	9.9	12.0	12.2	11.4	11.5	11.5	53.0
10	11.7	12.5	12.2	12.3	13.7	13.3	53.0	9.9	12.4	12.5	11.5	11.7	11.7	54.0
12	11.5	12.8	12.5	13.3	14.9	19.3	52.0	10.0	12.5	12.6	11.7	11.8	11.9	55.0
13	11.5	12.8	12.3	13.3	15.0	14.9	51.0	10.0	12.5	12.8	11.8	11.9	12.0	54.0
17	11.9	13.3	13.0	13.3	15.8	12.9	53.0	10.0	12.8	13.0	11.8	11.2	11.2	54.0
18	11.9	13.8	13.3	13.5	16.6	13.8	50.0	10.0	12.7	12.9	11.5	11.6	11.7	53.0
23	11.9	13.8	13.5	15.0	17.5	16.7	54.0	9.9	12.9	12.9	13.3	13.0	13.0	54.0
24	11.7	13.8	13.5	16.0	18.4	17.8	54.0	10.4	12.9	12.9	13.0	13.1	13.1	54.0
26	12.5	14.4	13.7	16.5	18.7	17.6	53.0	9.9	13.0	13.0	10.0	11.9	11.4	54.0
31	12.3	14.5	14.2	16.3	18.4	16.9	54.0	9.9	13.0	13.0	7.0	12.1	8.0	54.0
NOVEMBER														
1	12.5	15.0	14.6	8.5	8.5	8.3	54.0	6.5	11.2	11.2	8.2	8.5	8.5	54.0
9	14.0	14.5	14.0	10.2	10.3	10.4	51.0	10.7	11.8	12.0	10.6	10.6	10.6	53.0
10	13.8	14.3	13.7	10.5	10.7	10.8	51.0	10.5	12.0	12.0	11.0	10.9	10.8	53.0
13	14.0	14.2	14.0	8.0	8.0	8.0	53.0	10.7	11.0	11.5	8.2	8.2	8.2	52.0
15	10.5	10.5	10.5	9.1	9.3	9.1	54.0	10.0	11.1	11.0	8.8	8.9	8.9	54.0
21	10.9	10.5	10.5	9.4	9.5	9.3	53.0	9.0	11.0	11.0	9.0	9.0	9.0	53.0
22	11.0	11.2	11.2	9.8	9.9	9.9	53.0	9.2	11.5	11.5	7.0	9.5	9.5	55.0
DECEMER														
1	14.5	9.0	10.8	6.5	11.0	12.0	51.0	16.0	24.0	0.0	0.0	20.0	0.0	50.0
11	0.0	11.0	11.1	9.3	9.7	9.3	54.0	11.0	14.1	11.0	9.0	0.0	9.0	53.0
22	0.0	10.0	11.1	8.5	8.5	8.5	54.0	23.7	18.2	14.0	15.0	20.5	22.4	50.0

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APPENDIX C.2 TENSION DATA FOR WINTON SOIL YEAR 1978

	G R A S S							B A R E S O I L						
	DEPTH 200 MM			DEPTH 400 MM				DEPTH 200 MM			DEPTH 400 MM			
DATE	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H
MARCH														
6	10.6	10.5	10.5	9.4	6.3	9.1	43.0	8.4	10.0	10.2	9.4	40.4	5.3	50.0
13	9.7	10.0	10.0	8.2	6.3	8.3	43.0	9.6	10.0	9.7	8.8	34.3	5.3	50.0
15	8.6	9.4	8.6	8.3	5.6	8.2	43.0	9.5	10.0	10.3	9.0	8.7	8.5	50.0
20	7.7	9.2	8.2	7.7	6.6	7.4	43.0	7.5	9.7	9.7	8.0	8.3	8.0	50.0
21	8.8	9.6	9.1	8.6	7.9	8.2	45.0	8.5	10.2	10.6	9.0	8.9	8.9	48.0
28	8.4	9.3	9.1	8.3	7.5	7.9	47.0	7.8	9.9	10.1	8.7	8.6	8.5	50.0
29	7.5	9.8	9.9	8.5	8.8	8.7	47.0	7.5	9.2	8.5	7.6	6.8	7.5	50.0
30	7.3	8.8	8.5	7.9	7.0	7.2	44.0	7.2	9.8	9.8	8.7	8.5	8.3	50.0
31	8.1	10.4	10.6	10.3	9.2	9.1	44.0	8.8	9.7	9.8	8.9	7.5	8.0	50.0
APRIL														
3	9.4	9.7	10.0	7.8	7.8	8.3	48.0	9.4	9.9	10.1	8.4	8.6	8.1	49.0
4	9.7	9.9	10.0	8.6	8.2	8.9	46.0	8.7	10.2	10.5	8.7	8.7	8.8	49.0
6	10.3	10.5	10.6	9.6	9.5	9.5	46.0	10.3	10.7	11.0	9.8	9.5	9.5	49.0
7	10.0	10.5	10.8	10.8	10.0	9.8	46.0	11.2	11.1	11.2	10.0	9.1	9.8	49.0
10	16.3	14.5	14.3	10.8	9.8	9.9	45.0	10.5	11.9	11.0	14.0	11.0	10.1	49.0
11	13.9	11.8	12.0	11.0	9.2	10.0	45.0	10.2	10.7	11.0	11.5	10.5	10.3	49.0
12	10.8	10.8	10.9	10.3	11.0	10.6	45.0	11.8	12.3	11.6	11.4	7.8	10.4	49.0
13	10.8	11.3	11.6	11.3	11.0	11.0	45.0	11.6	11.6	11.4	11.6	7.0	10.6	49.0
14	11.0	10.8	11.4	9.0	11.2	9.0	45.0	12.3	11.3	12.3	10.0	7.0	7.8	49.0
15	10.4	10.5	11.0	9.0	10.5	9.0	45.0	12.7	11.3	11.8	9.7	7.0	6.5	49.0
16	10.2	10.5	10.9	9.8	10.4	9.2	45.0	10.9	10.8	11.0	10.2	7.0	9.2	49.0
17	10.8	10.8	11.0	11.4	5.4	10.3	46.0	10.5	10.6	11.4	10.8	10.6	10.0	50.0
18	10.1	10.5	11.0	10.4	10.3	9.8	46.0	10.7	10.8	10.9	10.8	5.0	10.2	50.0
19	10.5	10.5	10.8	11.3	11.0	10.2	45.0	10.8	10.9	11.2	12.0	5.3	10.7	50.0
21	11.3	10.8	11.0	12.5	11.7	11.2	45.0	11.0	11.0	11.2	13.5	5.6	11.5	50.0
22	11.5	11.4	9.0	12.5	0.0	0.0	49.0	8.0	11.3	11.3	13.5	6.4	11.8	50.0
23	11.4	11.6	9.0	15.0	0.0	0.0	49.0	8.5	11.0	11.0	14.5	6.4	12.2	50.0
24	8.5	11.2	11.2	14.9	6.4	13.1	45.0	11.8	11.9	9.0	6.0	6.1	7.2	50.0
25	8.6	11.3	11.5	16.0	12.9	12.9	45.0	11.6	11.7	11.6	12.9	12.4	7.7	48.0
26	0.0	12.4	12.3	10.8	13.7	9.0	45.0	8.5	12.2	11.5	16.8	14.0	12.2	48.0
27	12.6	12.3	9.8	13.8	13.5	9.0	45.0	8.5	12.0	11.5	14.0	14.5	13.7	47.0
28	8.4	9.8	9.0	7.5	7.2	8.0	45.0	9.5	9.6	9.9	7.8	7.2	7.2	50.0

APPENDIX C.2 TENSION DATA FOR WINTON SOIL YEAR 1978

DATE	GRASS							BARE SOIL						
	DEPTH 200 MM			DEPTH 400 MM				DEPTH 200 MM			DEPTH 400 MM			
	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H
MAY														
3	8.5	10.5	10.6	8.2	8.7	8.2	45.0	8.0	10.0	9.5	8.5	8.8	8.3	50.0
4	9.7	10.2	9.4	8.6	8.8	8.5	45.0	9.0	10.6	10.8	7.6	9.1	8.9	50.0
5	8.5	10.4	10.5	7.5	8.5	7.8	45.0	9.0	10.0	9.8	6.8	7.4	7.6	0.0
6	9.5	10.5	10.8	7.5	8.3	8.0	45.0	9.3	10.5	10.0	7.2	7.5	7.8	50.0
7	9.5	10.5	10.6	8.8	8.5	8.5	45.0	8.8	10.3	10.0	8.3	8.5	8.5	0.0
8	9.7	10.2	10.2	8.5	8.7	8.5	45.0	9.6	10.5	10.6	8.8	8.7	8.7	49.0
9	10.0	10.3	10.1	9.1	9.2	9.0	45.0	10.0	10.6	10.6	9.3	9.1	9.2	47.0
10	10.4	10.5	10.7	9.0	9.5	9.5	45.0	9.5	10.8	10.8	10.0	9.9	9.8	47.0
11	9.8	10.5	10.3	10.3	10.1	10.0	46.0	10.5	10.6	11.0	9.8	9.4	9.5	46.0
12	9.8	10.5	10.0	11.0	10.8	10.5	46.0	10.6	10.8	11.0	10.0	9.8	9.8	47.0
13	10.5	11.0	11.2	10.2	9.8	9.9	46.0	10.0	10.8	10.5	11.3	11.5	11.0	46.0
14	11.0	10.8	11.5	10.0	10.0	10.0	45.0	10.0	10.8	10.5	12.5	11.7	11.8	46.0
15	10.1	10.8	10.7	12.9	12.7	12.2	44.0	10.7	11.1	11.4	10.4	10.0	10.1	48.0
16	9.9	11.0	10.8	13.8	12.5	12.8	44.0	10.2	10.7	11.0	9.9	10.0	10.1	47.0
17	9.3	10.8	10.8	15.5	13.7	14.3	44.0	11.1	10.7	11.0	9.8	10.3	10.2	47.0
18	9.7	11.1	11.0	16.5	14.3	15.3	43.0	10.2	10.5	11.0	10.0	10.3	10.3	48.0
19	10.3	11.2	11.0	20.0	16.5	17.8	42.0	10.5	10.8	11.3	10.3	10.5	10.4	0.0
20	11.2	11.2	11.2	21.3	18.0	19.8	42.0	10.2	10.8	11.3	10.5	10.5	10.6	47.0
22	12.0	11.8	11.5	15.5	22.5	25.5	40.0	11.8	11.5	12.0	12.0	10.8	10.9	47.0
23	12.1	11.8	11.6	23.2	22.7	25.5	40.0	10.9	11.3	11.9	11.6	10.8	10.9	47.0
24	10.0	11.5	12.0	22.0	23.0	20.3	40.0	10.0	10.2	10.2	8.5	8.3	8.2	47.0
25	9.0	12.0	11.1	25.0	23.8	20.5	41.0	9.8	9.8	10.2	8.5	8.5	8.5	47.0
26	9.0	12.0	12.0	27.5	26.3	24.0	40.0	10.3	10.0	10.5	8.6	8.6	8.6	47.0
27	10.0	12.2	12.2	29.5	29.0	27.3	40.0	11.4	10.0	10.5	9.3	9.2	9.0	47.0
28	10.2	12.4	12.4	29.5	33.0	30.9	40.0	11.7	10.4	10.6	9.2	9.1	9.0	47.0
29	10.9	12.7	12.7	29.2	34.1	33.0	40.0	10.1	10.1	10.7	9.6	9.3	9.4	47.0
30	11.1	13.0	13.0	28.8	40.1	38.2	34.0	10.4	10.3	11.0	9.7	9.4	9.5	47.0
31	11.5	14.0	13.8	28.3	48.5	44.5	32.0	12.0	10.3	10.5	10.0	10.0	9.9	47.0

APPENDIX C.2 TENSION DATA FOR WINTON SOIL YEAR 1978

	GRASS							BARE SOIL						
	DEPTH 200 MM			DEPTH 400 MM				DEPTH 200 MM			DEPTH 400 MM			
DATE	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H
*****	****	****	****	****	****	****	****	****	****	****	****	****	****	****
JUNE														
1	14.4	14.3	14.1	28.3	52.6	48.6	36.0	10.5	10.5	11.1	11.0	9.9	10.0	46.0
2	18.2	15.0	15.0	27.5	58.2	51.6	35.0	11.5	10.3	10.5	11.8	10.2	10.2	46.0
3	22.5	16.5	16.5	27.3	62.7	55.0	34.0	11.5	10.4	10.5	12.2	10.5	10.3	46.0
4	24.3	18.2	18.0	26.5	65.4	57.3	33.0	11.8	10.4	11.0	12.4	10.6	10.5	45.0
5	24.4	20.7	20.3	26.5	68.6	60.0	32.0	11.6	10.6	11.5	13.2	10.9	10.9	45.0
6	24.6	23.9	23.9	0.0	70.4	62.2	32.0	12.4	10.8	11.7	13.7	11.4	11.3	45.0
7	25.0	27.9	28.0	19.0	0.0	64.5	38.0	13.0	16.0	11.5	14.5	12.0	11.8	45.0
9	26.2	37.0	39.0	0.0	0.0	66.2	38.0	10.0	11.2	11.5	16.5	13.2	12.8	45.0
10	26.5	43.6	45.5	0.0	0.0	66.5	38.0	10.0	11.2	11.6	16.8	13.6	13.3	45.0
11	0.0	55.0	55.0	0.0	0.0	67.5	38.0	10.8	11.3	12.0	17.5	14.1	14.0	45.0
12	0.0	60.0	59.0	50.0	0.0	0.0	40.0	11.6	11.6	12.2	18.2	14.4	14.3	45.0
13	67.5	64.4	62.3	33.4	33.4	48.7	35.0	8.5	9.6	12.2	17.6	16.0	15.1	47.0
14	72.8	68.5	62.5	58.0	30.0	63.0	35.0	9.0	9.8	12.5	19.0	17.0	15.8	47.0
15	74.1	70.9	68.9	0.0	11.8	66.5	50.0	9.0	11.5	12.4	20.0	17.5	16.5	47.0
16	74.6	72.8	71.2	0.0	0.0	68.0	48.0	8.9	12.0	12.5	21.2	18.4	17.3	48.0
19	74.9	25.5	57.2	0.0	71.3	68.8	39.0	8.6	12.1	12.5	23.3	21.6	18.9	47.0
20	74.5	73.8	66.0	37.5	62.7	26.0	38.0	8.8	11.0	7.7	7.7	7.3	9.8	48.0
21	73.5	73.9	69.7	59.0	78.8	42.8	35.0	9.0	12.9	8.2	7.5	7.8	7.9	46.0
22	0.0	72.8	71.7	11.0	68.6	46.1	40.0	9.5	10.0	8.5	7.5	8.0	8.5	48.0
26	41.8	73.9	35.9	11.5	66.2	40.3	40.0	9.9	10.4	8.6	7.6	7.1	8.5	48.0
27	38.5	46.2	39.8	21.5	64.8	39.8	45.0	9.0	10.6	9.5	7.3	6.8	9.0	47.0
28	41.2	43.8	41.3	25.7	64.4	39.8	43.0	9.0	10.5	8.6	7.3	6.9	9.0	47.0
29	47.3	43.0	41.7	31.9	62.8	39.9	42.0	9.2	11.0	8.7	7.5	6.7	9.3	46.0
30	51.2	42.9	41.8	36.6	62.6	40.8	42.0	9.7	11.0	8.9	7.5	7.1	9.5	46.0

APPENDIX C.2 TENSION DATA FOR WINTON SOIL YEAR 1978

DATE	G R A S S							B A R E S O I L						
	DEPTH 200 MM			DEPTH 400 MM				DEPTH 200 MM			DEPTH 400 MM			
DATE	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H	CEL1	CEL2	CEL3	CEL4	CEL5	CEL6	H
JULY														
3	52.0	42.5	41.8	36.0	62.6	40.0	41.0	9.5	11.0	8.7	7.5	7.1	9.3	46.0
4	53.3	41.3	41.5	7.0	51.8	10.7	46.0	8.3	10.0	8.5	7.5	7.3	8.3	48.0
6	21.9	41.6	42.0	10.0	10.2	9.7	50.0	8.5	10.4	8.8	7.5	7.0	8.8	48.0
7	24.8	41.6	42.2	10.4	10.3	10.2	51.0	8.9	10.6	8.8	7.6	7.0	9.2	48.0
10	28.2	40.5	41.6	17.4	14.4	14.9	49.0	9.8	11.0	9.0	7.2	6.4	9.9	48.0
11	29.3	39.7	41.7	19.0	15.9	17.1	49.0	10.0	11.5	9.5	8.0	7.9	10.0	48.0
12	32.0	39.2	41.5	21.5	16.8	18.4	48.0	9.7	11.2	8.7	7.5	7.0	10.4	48.0
13	33.7	36.5	41.5	25.2	19.6	20.8	48.0	10.0	10.9	8.7	8.3	6.9	10.5	48.0
14	35.0	32.4	41.5	31.2	23.0	23.6	47.0	9.6	14.0	9.0	8.0	0.0	10.9	48.0
17	36.0	16.3	40.7	52.4	38.9	35.2	45.0	9.0	11.5	10.2	13.8	12.4	12.3	48.0
18	34.0	12.1	40.4	58.5	45.0	39.6	45.0	9.2	11.6	0.0	14.6	13.0	12.9	46.0
20	68.2	57.8	39.4	64.5	52.0	46.3	36.0	9.7	12.0	0.0	16.5	14.4	14.0	48.0
21	69.6	58.8	39.4	66.0	54.0	48.6	36.0	9.0	12.0	7.8	17.0	15.0	14.5	47.0
24	70.3	64.0	48.2	67.5	58.7	54.0	34.0	9.4	12.0	9.8	18.2	16.6	15.9	46.0
25	70.3	65.6	38.2	67.6	60.2	56.0	36.0	9.2	12.1	9.9	19.0	17.8	17.6	45.0
27	70.9	66.9	0.0	48.6	60.8	57.5	38.0	10.5	12.3	10.6	14.5	15.9	13.2	45.0
28	71.0	67.8	0.0	29.5	62.5	58.7	0.0	10.0	12.7	9.8	14.4	15.5	13.5	45.0
AUGUST														
2	0.0	70.8	48.4	0.0	0.0	61.8	48.0	9.0	12.9	9.0	17.0	16.9	16.0	47.0
3	59.7	68.9	61.7	14.3	11.7	8.4	48.0	12.8	13.0	11.9	8.3	10.9	14.4	47.0
25	9.0	68.4	68.0	30.5	28.9	53.0	48.0	9.6	10.7	10.2	10.4	9.7	9.8	47.0
29	0.0	67.8	69.4	34.0	49.3	61.1	48.0	9.0	11.0	9.2	12.0	10.9	11.0	47.0
SEPTEMBER														
7	60.0	64.8	68.2	29.8	49.3	57.8	30.0	9.5	10.0	9.5	8.9	8.9	9.0	48.0
8	60.6	64.4	68.2	29.5	47.8	57.3	32.0	9.8	10.2	9.8	9.2	9.1	9.2	47.0
15	59.8	62.0	66.9	7.5	10.4	47.0	36.0	8.7	10.4	8.8	9.0	9.0	9.0	45.0
19	58.4	28.8	64.7	11.3	11.0	16.5	42.0	9.5	10.8	9.5	10.8	10.1	10.1	47.0
25	59.0	29.7	65.1	20.5	16.6	24.7	40.0	9.4	11.5	9.4	13.0	11.9	11.9	47.0
29	59.7	29.7	64.5	7.8	7.8	7.8	45.0	8.3	9.8	8.5	8.5	8.7	9.0	48.0
OCTOBER														
2	59.2	29.7	65.5	8.5	8.5	8.5	43.0	8.5	10.0	9.5	9.0	9.0	9.0	48.0
4	57.8	27.8	65.4	9.0	9.0	9.0	43.0	9.6	10.5	9.5	9.3	9.3	9.3	47.0
5	55.9	25.7	64.9	9.6	9.2	9.5	45.0	9.0	10.5	8.5	9.4	9.4	9.4	45.0
9	51.5	22.4	62.2	13.5	10.8	12.5	45.0	9.2	10.9	8.7	10.4	10.0	10.0	45.0
10	51.5	22.4	62.5	13.5	11.4	14.0	45.0	9.9	11.0	9.8	10.5	10.2	10.2	43.0
17	45.7	22.0	59.9	20.0	13.4	16.9	45.0	10.3	11.5	9.2	11.2	11.2	10.0	48.0
23	45.1	23.1	58.4	25.3	16.6	20.8	45.0	9.9	11.7	8.5	12.2	11.9	11.0	47.0
24	44.9	23.1	57.5	27.6	17.2	22.6	43.0	9.4	11.7	8.4	12.6	12.0	8.6	48.0
26	28.0	24.6	58.0	30.2	18.2	24.0	43.0	9.8	11.7	9.0	12.0	12.5	9.0	47.0
31	35.7	25.0	56.3	34.3	19.4	26.0	43.0	9.4	11.9	8.5	12.0	12.2	8.7	47.0
NOVEMBER														
1	37.5	26.2	55.6	35.0	7.3	8.3	48.0	9.7	9.7	9.0	8.2	9.0	8.1	47.0
21	8.0	9.5	9.0	8.4	8.2	8.0	54.0	7.6	9.8	10.2	8.3	8.2	7.4	48.0
16	7.9	10.9	9.0	8.2	8.2	8.0	53.0	7.5	9.6	10.0	7.9	7.9	7.4	48.0
DECEMBER														
5	11.0	10.9	10.9	8.5	8.7	8.8	50.0	8.7	9.9	8.7	8.2	7.3	6.0	49.0
11	8.0	9.2	8.9	8.4	8.2	8.0	55.0	6.0	9.5	7.0	8.0	7.5	0.0	50.0
22	7.0	11.0	9.5	8.0	8.4	8.4	53.0	16.4	10.5	12.9	12.0	16.0	14.5	48.0

APPENDIX D

S.M.C.P.P.

APPENDIX D.1: SOIL MOISTURE CONTENT PREDICTION PROGRAM (SMCPP)

```
C THIS PROGRAMME CALCULATES SOIL MOISTURE CONTENTS FOR EVERY
C DAY OF THE YEAR  FOR TEN YEARS FROM METEROLOGICAL DATA
C THIS ALSO CALCULATES SOIL WORKDAY
C GRAPHS OF SOIL MOISTURE AGAINST DAYS OF THE MONTH CAN BE OBTAIND
C FROM CHANNEL 11
C A TABLE OF NUMERICAL RESULTS COULD BE OBTAIND FROM
CHANNEL 4 AND A WORKDAY TABLE FROM CHANNEL 6
C DAILY HOURS OF SUNSHINE AND PRECIPITATION ARE READ FROM
CHANNEL 9
C VARIABLE NAMES
C      PE    =MONTHLY POTENTIAL EVAPORATION
C      MNTH  =LENGTH OF MONTH IN DAYS
C      DPE   =DAILY POTENTIAL EVAPORATION
C      LDCF  =LENGTH OF DAY CORRECTION FACTOR
C      DS    =DURATION OF SUNSHINE
C      RDCF  =RAINY DAY CORRECTION FACTOR
C      TM    =TEMPERATURE
C      PPT   =PRECIPITATION
C      DL    =DAYLENGTH
C      DLIND =INDEX FOR DL
C      NDS   =NO. OF SUCCESIVE RAINY DAYS
C      PTAB&PPTFAC ARE USED TO DETERMINE RUN-OFF ALLOWANCE
C      WD    =WORK DAY ,SET TO N FOR NONE WORK DAY,SET TO W FOR WORK DAY
C      DM    =DRAINAGE AT SATURATION MM/DAY
C      DF    =DRAINAGE AT FIELD CAPACITY MM/DAY
C      MM    =MOISTURE CONTENT AT SATURATION MM IN A GIVEN DEPTH
C      FCAP  =SOIL MOISTURE CONTENT AT FIELD CAPACITY
       DIMENSION PTAB(3),PPTFAC(3),RFAC(3),AIY(365)
       DIMENSION AIM(365),AID(365),ASMC(365)
       DIMENSION DL(24,36),PPT(31,12,10),DS(31,12,10),DPE(12,10)
       INTEGER*4 IDENT(20),IXY(31),MNTH(12),DLIND(24),SCOND
       REAL*4 NP,LDCF,MM
       INTEGER*2 LINE(32),SPACE2,CAPT(10)
       COMMON/WEATHR/ DL,PPT,DS,MNTH,DLIND,DPE
       DATA IXY/1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,
      118,19,20,21,22,23,24,25,26,27,28,29,30,31/
       DATA RFAC/0.75,0.65,0.55/
       DATA LAST,SPACE2/'LAST','  '/
       DATA PTAB,PPTFAC/0,25.4,50.8,1,0.75,0.5/
C READ IN VALUES FROM TABLES VIA SUBROUTINES
       CALL THORNS
       WRITE(6,999)
  999 FORMAT(1H ,' THORNS ENDED' )
       CALL DAYLNG
       WRITE(6,998)
  998 FORMAT(1H ,' DAYLNG ENDED' )
       CALL CLIMAT
C READ IN THE LATITUDES AND FIELD CAPACITY AND CAPTION FOR GRAPHS
       READ(5,921) CAPT
  921 FORMAT(10A4)
       READ(5,500)LAT,FCAP
```

APPENDIX D.1: (CONTINUED)

```
C CHECK THAT THE LATITUDE IS HELD IN THE INDEX
      DO 20 I=1,24
      IF(LAT.EQ.DLIND(I)) GOTO 25
   20 CONTINUE
C LATITUDE WAS NOT FOUND SO TERMINATE PROGRAM
      WRITE(6,604)LAT,DLIND
      STOP
C SET LATIT TUDE INDEX
   25 LINX=I
C  CALCULATE DRAINAGE COEFFICIONTS
   30 READ(5,502,END=450)IDENT,DM,DF,MM,BD,NY
      IF(IDENT(1).EQ.LAST) STOP
      COEFF1=(ALOG(DM/DF))/(MM-FCAP)
      COEFF2=(ALOG(DM)-(MM*COEFF1))
C SET INITIAL VALUES
      WRITE(4,445)IDENT
  445 FORMAT(1H1,20A4/
     1'    DATE      DPT      ET    DRAIN   RUNOFF   SMEX     ',
     1'   DRY   RDCF    LDCF   DPE   SMC      SMD     FCAP')
      SMEX=0.0
      NDS=0
      SMCP=FCAP
      SMD=0
      DRY=1.0
      RDCF=0.6
      LDCF=0.5
C NOW CALCULATE TO DETERMINE SOIL MOISTURE CONTENT
C    IY IS YEAR IDEX,IM IS MONTH INDEX
      DO 300 IY=1,NY
      K=1
      SMD=0
      SMCP=FCAP
      DO 280 IM=1,12
C ESTABLISH NO OF DAYS IN CURRENT MONTH AND CALCULATE DRAINAGE
      IN=MNTH(IM)
      DO 260 ID=1,IN
      DRAIN=EXP((COEFF1*SMCP+COEFF2)*2.30259)
      IF(DRAIN.GT.30) DRAIN=30
C CALCULATE LENGTH OF DAY FACTOR,LDCF
C FIND WHICH THIRD OF THE MPNTH THE DAY IS IN
      I3=ID/10+1
      IF(I3.GT.3) I3=3
C NOW FIND THE DAY LENGTH FOR THIS LATITUDE FROM THE SMITHSOWIAN TABLE
C IF THE POSITION IN THE TABLE FOR THIS LATITUDE(LINX)
      IP=(IM-1)*3+I3
C NO OF POSSIBLE HOURS OF SUNSHINE (NP)
      NP=DL(LINX,IP)
C NOW LOOK UP THE ACTUAL AMOUNT OF SUNSHINE FOR THIS DAY,DSHN
      DSHN=DS(ID,IM,IY)
      LDCF=DSHN/NP
C SET TO 1 FOR JUNE-AUGUST INCLUSIVE
      IF((IM.EQ.6).OR.(IM.EQ.7).OR.(IM.EQ.8)) LDCF=1
C NOW DETERMINE THE RAINY DAY CORRECTION FACTOR RDCF
C LOOK UP PRECIPITATION FROM TABLE
      DPT=PPT(ID,IM,IY)
      RDCF=1
      IF(DPT.LT.0.0001) GOTO 40
```

APPENDIX D.1: (CONTINUED)

```
C INCREMENT NO. OF SUCCESIVE RAINY DAYS
      NDS=NDS+1
      IF(NDS.GT.3) NDS=3
      RDCF=RFAC(NDS)
      GOTO 45
   40 NDS=0
C NOW CALCULATE RUN OFF
   45 RUNOFF=0.0
      IF(FCAP.LT.50.0) GOTO 50
      A=SMCP/(BD*300.0)
      B=A-0.18
      SS=B*BD*1500.0
      Q1=(DPT-(DPT*(615.0356-2.847*SS))/(DPT+529.437-2.437*SS))*0
      Q2=(DPT-(DPT*(219.6338-0.904*SS))/(DPT+134.0358-0.494*SS))*0
      IF(Q1.LT.0) Q1=0
      IF(Q2.LT.0) Q2=0
      IF((SS.LT.198.1).AND.(SS.GT.0.0)) RUNOFF=Q1
      IF(SS.GE.198.1) RUNOFF=Q2
C NOW CALCULATE DRYNESS FACTOR,DAILY EVAPOTRANSPIRATION,& SOIL MOISTURE
C DEFICIENCY
   50 ET=DPE(IM,IY)*DRY*RDCF*LDCF*0.80
C NOW CALCULATE SOIL MOISTURE CONTENT
      SMC=DPT+SMCP-ET-DRAIN-RUNOFF
      IF(SMC.GT.MM) SMC=MM
      IF(SMC.LT.0) SMC=0.0
      SMD=FCAP-SMC
      SMEX=0.0
      IF(SMD.LT.0.0) SMEX=SMD*(-1.0)
      AIY(K)=IY
      AIM(K)=IM
      AID(K)=ID
      ASMC(K)=SMC
      K=K+1
      WRITE(4,444)ID,IM,IY,DPT,ET,DRAIN,RUNOFF,SMEX,
     1DRY,RDCF,LDCF,DPE(IM,IY),SMC,SMD,FCAP
  444 FORMAT(1H ,3I3,12F8.3)
C SET UP DRYNESS FACTOR FOR NEXT DAYS VALUES
      DRY=1
      IF(SMD.GT.2.0*20.4) DRY=0.0
      IF(SMD.GT.5.8*25.4)DRY=0.00
      IF(SMD.GT.8.4*25.4) DRY=0.0
      SMCP=SMC
  260 CONTINUE
  280 CONTINUE
      CALL GRAPH(AIY,AIM,AID,ASMC,CAPT)
  300 CONTINUE
      GOTO 30
  450 STOP
  500 FORMAT(I3,4X,F8.2)
  502 FORMAT(20A4/,F5.2,F8.4,F8.2,F8.4,I2)
  604 FORMAT(1H ,' LATITUDE SPECIFIED: ',I4,' NOT IN INDEX: '/1H ,24I3)
      END
      BLOCK DATA
      INTEGER*4 MNTH(12),DLIND(24)
      REAL*4 DL(24,36),PPT(31,12,10),DS(31,12,10),DPE(12,10)
      COMMON/WEATHR/ DL,PPT,DS,MNTH,DLIND,DPE
      DATA MNTH/31,28,31,30,31,30,31,31,30,31,30,31/
      END
```

APPENDIX D.1 (CONTINUED)

```
C SUBROUTINE 'DAYLNG'
C READ DAY LENGTH VALUES FROM SMITHSONIAN TABLES INTO THE 24X36 ARRAY DL
C DLIND HOLDS THE ARRAY POINTER FOR A PARTICULAR LATITUDE. THERE ARE
C 3 DAY LENGTH VALUES PER MONTH-FIRST 10 DAYS, SECOND 110 DAYS AND THE REMAINDE
C OF THE MONTH. BY MANIPULATING THE TABLES THE VALUES CAN BE USED FOR SOUTHERN
C HEMISPHERE CALCULATIONS BUT THIS FACILITY IS NOT YET INCLUDED

      SUBROUTINE DAYLNG
      DIMENSION SMITH(36),DL(24,36),PPT(31,12,10),DS(31,12,10),
     1DPE(12,10)
      INTEGER*4 DLIND(24),MNTH(12)
      COMMON/WEATHR/ DL,PPT,DS,MNTH,DLIND,DPE
C INITIALISE THE INDEX
      DO 10 I=1,24
   10 DLIND(I)=-1
      I=0
   15 READ(7,700,END=50)ILAT,SMITH
      IF(ILAT.LT.0) GOTO 50
C LOOK FOR THIS LATITUDE IN THE INDEX
      IF(I.EQ.0) GOTO 25
      DO 20 J=1,I
      IF(ILAT.NE.DLIND(J)) GOTO 20
      WRITE(6,600) ILAT
      STOP
   20 CONTINUE
C NEW LATITUDE VALUES
   25 I=I+1
C 24 LATITUDE VALUES IS MAXIMUM
      IF(I.LT.25) GOTO 30
      WRITE(6,601)
      STOP
   30 DLIND(I)=ILAT
C COPY SMITHSONIAN VALUES INTO DAYLENGTH ARRAY
      DO 40 J=1,36
   40 DL(I,J)=SMITH(J)
      GOTO 15
   50 WRITE(6,602)I
      RETURN
C FORMAT STATEMENTS
  700 FORMAT(I2,12(1X,F5.0),2(/12(1X,F5.0)))
  600 FORMAT(1H0,' VALUES FOR LATITUDE ',I4,' ARE ALREADY READ IN')
  601 FORMAT(1H0,' INDEX FULL - MAXIMUM IS 24 LATITUDE VALUES ')
  602 FORMAT(1H ,' END OF SUBROUTINE DAYLNG ',I4,' LATITUDE VALUES ')
      END
```

APPENDIX D.1: (CONTINUED)

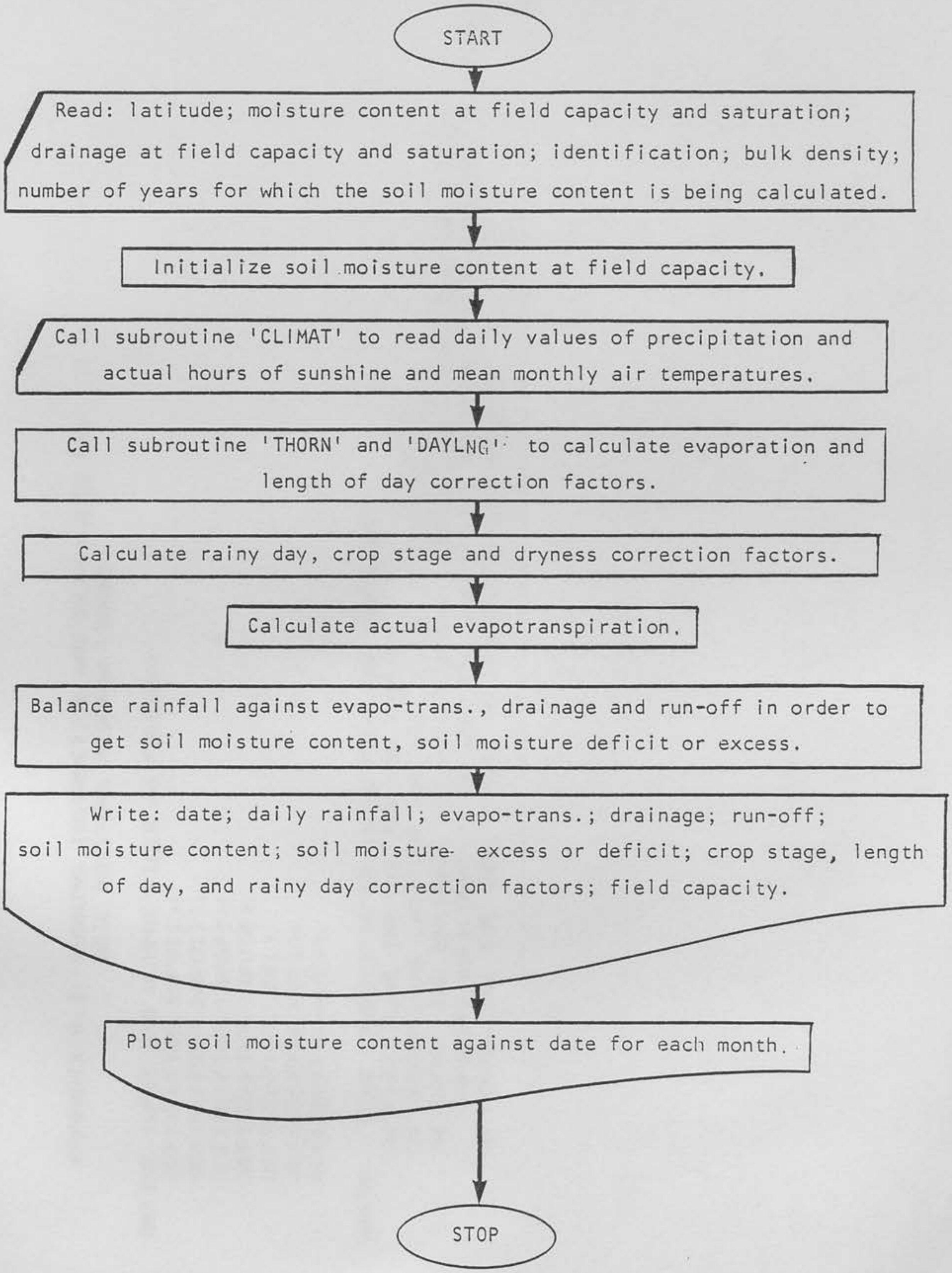
```
C SUBROUTINE THORNS
 C CALCULATE THORNWAITE CORRECTION FOR POTENTIAL EVAPORATION
 C INPUT DATA VALUES -YEAR INDEX(1-10) FOLLOWED BY 12 MONTHLY VALUES OF TEMP
 C IN CENTIGRADE.DECIMAL POINTS MUST BE PUNCHED -1 AS YEAR INDEX TERMINATER


      SUBROUTINE THORNS
      INTEGER*4 MNTH(12),DLIND(24)
      DIMENSION DL(24,36),PPT(31,12,10),DS(31,12,10),DPE(12,10),
     1CARD(12),X(12)
      COMMON/WEATHR/ DL,PPT,DS,MNTH,DLIND,DPE
   10 READ(8,800)INDY,CARD
      IF(INDY.LT.0) RETURN
      X1=0.0
      DO 20 I=1,12
      IF(CARD(I).GT.0) X1=X1+(CARD(I)/5.0)**1.514
   20 CONTINUE
      X2=X1*X1
      X3=X2*X1
      A=6.75E-7*X3-7.7E-5*X2+0.01792*X1+0.49239
      DO 30 I=1,12
      DPE(I,INDY)=0.0
      IF(CARD(I).GT.0.0) DPE(I,INDY)=(1.6*(10.0*CARD(I)/X1)**A)
     1/MNTH(I)*10.0
   30 CONTINUE
      GOTO 10
  800 FORMAT(I2,12F6.0)
      END
```

APPENDIX D.1: (CONTINUED)

```
 C SUBROUTINE 'CLIMAT'
C READ IN 10 YEARS' VALUES OF DAILY PRECIPITATION AND SUNSHINEPRECIPITATION
C IS IN EITHER INCHES & TENTHS OR MM. SUNSHINE IS IN HOURS AND TENTHS. IMPERIA
C MEASURE IS DENOTED BY IM IMMEDIATELY AFTER THE MONTH NO,METRIC BY ME. DATA
C STARTS AT JANUARY DAY 1 AND TEN YEARS VALUES ARE READ IN AT A TIME.
C FIRST READ IN THE YEAR NOS. AND UNITS TO BE USED
      SUBROUTINE CLIMAT
      INTEGER*4 MNTH(12),DLIND(24),ICARD(20)
      DIMENSION SCARD(21),DL(24,36),PPT(31,12,10),DS(31,12,10),
     1DPE(12,10)
      COMMON/WEATHR/DL,PPT,DS,MNTH,DLIND,DPE
      EQUIVALENCE(ICARD(1),IYEAR)
      DATA IMP/'IM'/
      READ(9,900)ICARD
      WRITE(6,666)ICARD
  666 FORMAT(1H ,' CLIMAT ENTERED ',10(A4,1X,A2))
      DO 40 M=1,12
C READ MONTH NAME
      READ(9,902)MNAME
C      WRITE(6,902)MNAME
      ICNT=0
C READ IN 1 MONTHS VALUES IN DAY ORDER
   10 READ(9,901)SCARD
C      WRITE(6,903)SCARD
      IDAY=INT(SCARD(1)+0.5)
      IF(SCARD(1).LT.00.0) GOTO 25
      ICNT=ICNT+1
      IF(IDAY.NE.ICNT) GOTO 50
C TRANSFERS VALUE TO PRECIPITATION & SUNSHINE ARRAYS
      K1=2
      K2=3
      K3=0
      DO 20 J=1,10
      FAC=10.0
      K3=K3+2
C CONVERT TO MM IF RAINFALL WAS IN INCHES
      IF(ICARD(K3).EQ.IMP) FAC=25.4
      PPT(IDAY,M,J)=SCARD(K1)*FAC
      DS(IDAY,M,J)=SCARD(K2)
      K1=K1+2
   20 K2=K2+2
      GOTO 10
C CHECK THAT CORRECT NO. OF VALUES HAVE BEEN READ FOR THIS MONTH
   25 IF(ICNT.EQ.MNTH(M)) GOTO 40
      IF((M.EQ.2).AND.(ICNT.EQ.29)) GOTO 40
      WRITE(6,600)M,MNTH(M),ICNT
   40 CONTINUE
      RETURN
   50 WRITE(6,601)IDAY,ICNT,M
      STOP 6
  900 FORMAT(3X,10(A4,1X,A2))
  901 FORMAT(F2.0,1X,10(F3.2,F3.1,1X))
  902 FORMAT(A4)
  903 FORMAT(1H ,F4.0,20F5.2)
  600 FORMAT(1H ,' DAYS RECORDED FOR MONTH: ',I3,' SHOULD BE: ',I3,
     1' BUT WAS: ',I4/)
  601 FORMAT(1H ,' DAY NO. READ WAS: ',I3,' WHEN ',I3,' WAS EXPECTED.',
     1'MONTH: ',I3/)
      END
```

APPENDIX D.2: THE FLOW CHART OF SOIL MOISTURE PREDICTION MODEL



APPENDIX D.3: RUNNING INSTRUCTION AND DATA FILES FOR SOIL MOISTURE PROGRAM (SMCPP)

```
DEFINE INPUT AND OUTPUT FILES AS FOLLOWS:
   DEFINE(FT05,INPUT1);
   DEFINE(FT07,INPUT2);
   DEFINE(FT08,INPUT3);
   DEFINE(FT09,INPUT4);
   DEFINE(FT04,OUT1);
   DEFINE(FT06,OUT2);
   DEFINE(FT11,OUT3).

WHERE:  FILE 'INPUT1' IS AN INPUT FILE AND CONTAINS:
      ON FIRST LINE THE CAPTION FOR GRAPHS;
      ON SECOND LINE LATITUDE AND SOIL FIELD CAPACITY;
      ON THIRD LINE DRAINAGE AND SOIL MOISTURE CONTENT AT SATURATION AND FIELD
         CAPACITY,BULK DENSITY OF THE SOIL AND NUMBER OF YEARS FOR WHICH DATA IS AVAILABLE;
      ON FORTH LINE THE WORD 'LAST' TO TERMINATE DATA READING.

THE FOLOWING IS AN EXAMPLE FILE.

 EXAMPLE:

   CAPTION
 56      110.00
MAC SOIL 1978 TEST RUNBARE
26.700.700000157.00001.29    01
LAST
 0       0         0

FILES 'INPUT2', 'INPUT3' AND 'INPUTT4' ARE DATA FILES AS GIVEN IN APPENDICES D.6,D.4 AND D.5;
            FILES 'OUT1'AND 'OUT2' ARE OUTPUT FILES AS GIVEN IN APPENDICES D.7 AND D.8
           AND FILE 'OUT3' IS A FILE CONTAINING THE PROGRAMME'S PROGRESS REPORT AND ERROR MESSAGES.
```

APPENDIX D.4

MEAN MONTHLY AIR TEMRATURE DATA FOR THE BUSH ESTATE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
1	4.0	3.9	5.3	8.3	10.3	11.3	14.5	13.9	11.5	10.0	5.2	5.0
2	4.7	4.2	7.3	10.5	14.8	16.1	15.3	12.2	9.7	5.3	1.1	
3	5.9	5.2	4.9	6.6	10.7	12.8	13.9	14.1	10.9	7.2	5.5	6.5
4	3.45	-0.45	1.40	5.35	8.45	12.35	14.60	14.60	11.85	11.40	2.90	2.10
5	2.05	1.25	3.15	6.90	9.95	12.75	12.50	13.90	12.00	8.90	4.90	3.40
6	3.15	3.85	4.00	6.25	9.45	10.40	14.30	13.15	12.40	9.25	4.80	6.35
7	2.65	2.80	4.55	7.20	9.20	10.15	13.45	12.65	9.55	9.00	4.55	4.60
8	3.40	2.95	5.55	5.39	9.95	12.98	13.60	13.60	11.90	7.76	4.28	3.49
9	4.60	3.48	3.90	5.54	9.75	11.66	12.89	13.10	9.95	6.69	4.75	5.63
10	4.36	3.14	3.28	2.94	7.64	12.41	14.70	16.08	10.83	8.82	4.78	5.31
-1												

APPENDIX D.5: AN EXAMPLE INPUT FILE FOR SOIL MOISTURE AND WORKDAY PROGRAMMES CONTAINING:
ON FIRST LINE THE YEAR AND A CODING TO IDETIFY THE UNITS OF THE DATA I.E.
ME FOR METRIC AND IM FOR IMPERIAL;
ON SECOND LINE THE MONTH NAME;
ON THIRD AND SUBSEQUENT LINES DAY NUMBER, RAINFAL AND SUNSHINE HOURS
FOR EACH YEAR UP TO 20 YEARS.

EXAMPLE: FOR MONTH JANUARY YEARS 1969_1978

```
0001969 IM1970 IM1971 ME1972 ME1973 ME1974 ME1975 ME1976 ME1977 ME1978
JANUARY
 1 000010 000000 000022 022000 012000 000002 000007 016000 000000 002002
 2 000050 005000 000000 016000 036000 000046 005010 194000 000055 094022
 3 001016 000062 000019 019000 001052 000000 001010 001054 007016 074005
 4 005012 000062 000000 010000 000006 048000 015008 034000 024000 011023
 5 014033 028050 000000 010000 000001 049006 013000 045000 003000 000000
 6 006000 000059 057000 000016 000000 007013 001020 011000 000025 000000
 7 032000 000020 009013 004000 000000 025000 000000 004000 000038 000011
 8 000000 021000 013000 000000 000000 054000 001000 002026 006000 090021
 9 000037 015000 000004 000000 000000 001048 065000 007002 007050 093000
10 006000 003000 000005 022001 000000 060003 041005 004000 050016 000001
11 004003 025000 000049 036000 000053 031008 002003 000005 000046 003049
12 022000 022000 000000 040023 000040 015026 071000 007000 000000 006007
13 005000 000038 002000 007015 000000 012012 030000 028000 071000 000029
14 006013 011000 003000 004032 020000 019002 081003 000031 432000 017000
15 000019 037000 000000 003000 016002 014011 075000 000000 015000 025000
16 006013 005001 002018 004000 000040 062000 056040 001037 000028 000000
17 019000 013000 000008 019000 000060 017000 001002 003003 000000 015043
18 031000 003000 004009 112000 002057 006000 000018 057009 015000 004000
19 000013 002000 002030 009046 000000 000000 045005 094000 003022 009000
20 049000 000027 033000 021048 033000 001067 001051 060006 011000 009000
21 042013 000008 002000 006040 160000 000000 134034 046007 010000 006001
22 000045 000034 039001 007004 010052 010005 146008 034034 002036 042000
23 001001 000000 019000 069000 013000 072045 044001 001058 000000 000006
24 002000 002000 084036 005041 001011 000012 047037 000023 000034 000021
25 001005 000028 036004 014040 055001 074013 105016 006045 249000 004001
26 000000 022000 001000 049000 030022 027005 033002 035000 026000 112000
27 005016 000029 000000 007009 001000 052061 074000 000032 003000 107000
28 000027 000000 136000 013028 000003 010004 004015 000000 000058 014000
29 003062 009000 052000 000006 021003 023062 130011 000000 000069 048063
30 019006 000000 000000 030020 002034 021004 016051 000056 059004 000007
31 000061 001041 000013 000000 013000 001065 035023 000004 000048 000000
-1
FEBRUARY
```

APPENDIX D.6 SMITHSONIAN TABLE

LAT	JANUARY			FEBRUARY			MARCH			APRIL			MAY			JUNE		
0	12.12	12.12	12.12	12.12	12.12	12.12	12.12	12.12	12.12	12.12	12.12	12.12	12.12	12.12	12.12	12.12	12.12	12.12
5	11.85	11.87	11.88	11.93	11.96	12.00	12.04	12.08	12.13	12.18	12.22	12.27	12.32	12.35	12.37	12.40	12.41	12.42
10	11.56	11.61	11.66	11.73	11.81	11.90	11.97	12.06	12.15	12.27	12.35	12.43	12.52	12.57	12.63	12.68	12.70	12.72
15	11.28	11.34	11.42	11.53	11.66	11.78	11.90	12.04	12.18	12.33	12.47	12.60	12.72	12.83	12.91	12.98	13.01	13.02
20	10.97	11.06	11.17	11.33	11.50	11.67	11.82	12.01	12.20	12.42	12.60	12.77	12.93	13.08	13.20	13.28	13.33	13.35
25	10.65	10.76	10.92	11.11	11.33	11.55	11.75	11.98	12.23	12.50	12.74	12.97	13.17	13.35	13.50	13.62	13.68	13.68
30	10.30	10.42	10.63	10.88	11.13	11.42	11.67	11.97	12.27	12.58	12.88	12.17	13.44	13.66	13.85	13.99	14.07	14.08
35	9.90	10.07	10.30	10.62	10.95	11.28	11.58	11.97	12.30	12.70	13.07	13.40	13.71	14.00	14.23	14.41	14.50	14.50
40	9.45	9.65	9.93	10.32	10.70	11.12	11.47	11.92	12.35	12.83	13.25	13.66	14.04	14.38	14.67	14.88	15.00	15.00
42	9.25	9.45	9.78	10.19	10.60	11.05	11.42	11.90	12.37	12.88	13.35	13.78	14.20	14.55	14.85	15.10	15.22	15.23
44	9.02	9.25	9.60	10.04	10.49	10.97	11.37	11.86	12.39	12.94	13.43	13.92	14.35	14.74	15.07	15.33	15.47	15.47
46	6.78	9.05	9.42	9.89	10.38	10.90	11.32	11.87	12.42	13.00	13.53	14.04	14.52	14.95	15.29	15.58	15.68	15.75
48	8.54	8.82	9.21	9.73	10.25	10.82	11.27	11.85	12.43	13.07	13.65	14.19	14.71	15.17	15.54	15.68	16.02	16.03
50	8.26	8.57	8.99	9.55	10.12	10.72	11.21	11.83	12.47	13.16	13.76	14.34	14.90	15.41	15.82	16.17	16.35	16.35
52	7.95	8.27	8.75	9.37	9.97	10.61	11.14	11.83	12.49	13.22	13.89	14.52	15.12	15.67	16.13	16.51	16.70	16.72
54	7.60	7.96	8.47	9.14	9.81	10.52	11.08	11.80	12.53	13.32	14.02	14.72	15.37	15.97	16.47	16.89	17.11	17.12
56	7.12	7.61	8.17	8.91	9.63	10.39	11.00	11.78	12.57	13.42	14.18	14.94	15.65	16.47	16.87	17.35	17.57	17.60
58	6.74	7.21	7.80	8.63	9.42	10.25	10.92	11.77	12.60	13.52	14.35	15.17	15.96	16.70	17.32	17.86	18.13	18.15
60	6.22	6.72	7.44	8.33	9.20	10.10	10.82	11.73	12.66	13.65	14.57	15.44	16.31	17.12	17.96	18.47	18.80	18.83
61	5.90	6.46	7.22	8.16	9.07	10.02	10.77	11.72	12.67	13.71	14.67	15.60	16.52	17.40	18.17	18.85	19.22	19.22
62	5.53	6.16	6.97	7.98	8.93	9.93	10.72	11.71	12.70	13.78	14.78	15.77	16.73	17.67	18.53	19.27	19.68	19.69
63	5.13	5.82	6.70	7.78	8.80	9.83	10.65	11.68	12.73	13.87	14.90	15.93	16.97	17.98	18.90	19.77	20.22	20.25
64	4.68	5.45	6.40	7.55	8.63	9.73	10.60	11.67	12.77	13.95	15.03	16.13	17.23	18.33	19.37	20.35	20.92	20.98
65	4.15	5.05	6.08	7.32	8.47	9.62	10.53	11.67	12.80	14.03	15.18	16.35	17.53	18.72	19.88	21.08	21.87	21.97

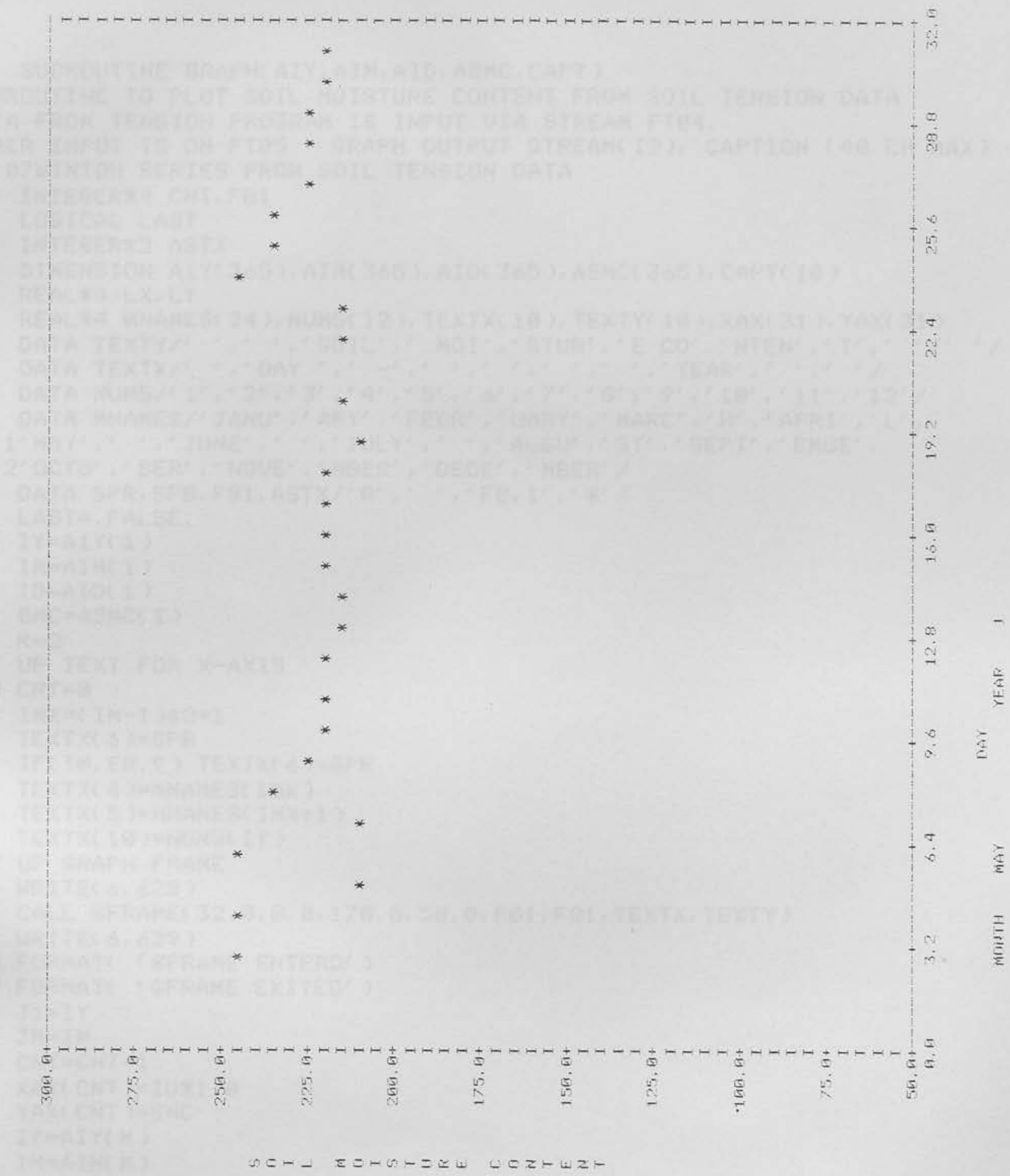
LAT	JULY			AUGUST			SEPTEMBER			OCTOBER			NOVEMBER			DECEMBER		
0	12.12	12.12	12.12	12.11	12.10	12.10	12.11	12.11	12.11	12.12	12.12	12.12	12.12	12.12	12.12	12.12	12.12	12.13
5	12.40	12.38	12.36	12.33	12.28	12.23	12.19	12.16	12.10	12.05	12.02	11.97	11.92	11.90	11.87	11.85	11.83	11.83
10	12.68	12.64	12.60	12.53	12.45	12.37	12.27	12.17	12.08	12.00	11.91	11.83	11.75	11.67	11.61	11.58	11.54	11.54
15	12.98	12.94	12.85	12.73	12.62	12.50	12.35	12.22	12.08	11.95	11.82	11.67	11.55	11.43	11.35	11.28	11.22	11.24
20	13.30	13.23	13.12	12.97	12.83	12.62	12.45	12.25	12.07	11.88	11.70	11.52	11.35	11.19	11.07	10.97	10.93	10.93
25	13.63	13.56	13.41	13.22	13.02	12.82	12.55	12.31	12.07	11.82	11.58	11.35	11.12	10.93	10.78	10.67	10.60	10.60
30	14.02	13.89	13.72	13.49	13.23	12.96	12.65	12.34	12.05	11.76	11.47	11.18	10.89	10.65	10.47	10.32	10.23	10.22
35	14.45	14.29	14.07	13.78	13.48	13.16	12.77	12.42	12.07	11.68	11.33	10.98	10.63	10.34	10.10	9.93	9.82	9.82
40	14.92	14.74	14.48	14.13	13.77	13.37	12.91	12.48	12.06	11.60	11.18	10.77	10.33	9.88	9.70	9.84	9.35	9.35
42	15.12	14.92	14.67	14.29	13.90	13.46	12.97	12.51	12.06	11.57	11.12	10.67	10.22	9.83	9.52	9.29	9.15	9.15
44	15.37	15.17	14.87	14.44	14.02	13.57	13.03	12.54	12.03	11.64	11.04	10.57	10.07	9.67	9.32	9.00	8.90	8.90
46	15.62	15.40	15.07	14.62	14.17	13.68	13.11	12.57	12.04	11.51	10.97	10.45	9.92	9.48	9.11	8.83	8.68	8.65
48	15.91	15.66	15.30	14.82	14.32	13.80	13.18	12.61	12.03	11.46	10.88	10.33	9.75	9.28	8.86	8.57	8.41	8.37
50	16.22	15.95	15.55	15.03	14.50	13.92	13.27	12.67	12.03	11.41	10.80	10.21	9.58	9.07	8.63	8.30	8.12	8.09
52	16.56	16.27	15.83	15.26	14.67	14.06	13.35	12.69	12.02	11.37	10.70	10.07	9.37	8.82	8.37	8.00	7.82	7.77
54	16.95	16.63	16.15	15.52	14.88	14.21	13.44	12.74	12.02	11.32	10.60	9.91	9.17	8.56	8.05	7.66	7.42	7.40
56	17.40	17.04	16.50	15.81	15.12	14.38	13.55	12.81	12.02	11.26	10.48	9.74	8.95	8.26	7.71	7.26	7.00	6.97
58	17.92	17.52	17.91	16.15	15.38	14.57	13.67	12.85	12.02	11.20	10.37	9.54	8.68	7.93	7.32	6.81	6.52	6.48
60	18.57	18.07	17.38	16.52	15.67	14.81	13.81	12.92	12.02	11.12	10.22	9.33	8.38	7.57	6.85	6.28	5.93	5.90
61	18.95	18.40	17.67	16.73	15.83	14.91	13.89	12.93	12.02	11.07	10.15	9.22	8.21	7.34	6.60	5.98	5.61	5.57
62	19.40	18.77	17.98	16.97	16.02	15.05	13.97	13.00	11.98	11.03	10.05	9.08	8.03	7.12	6.30	5.62	5.22	5.18
63	19.90	19.19	18.30	17.23	16.21	15.25	14.05	13.03	12.00	11.00	9.97	8.95	7.83	6.87	5.97	5.25	4.80	4.73
64	20.52	19.67	18.68	17.50	16.42	15.33	14.15	13.08	12.00	10.95	9.87	8.80	7.63	6.58	5.62	4.82	4.30	4.27
65	21.30	10.16	19.10	17.82	16.65	15.50	14.25	13.12	12.00	10.90	9.77	8.65	7.40	6.27	5.22	4.28	3.71	3.65

APPENDEX D.7: OUTPUT FROM SOIL MOISTURE MODEL - DAILY SOIL MOISTURE TABLE

TEST SOIL 1978 TEST RUN GRASS

DAY	MONTH	YEAR	PRECIPITATION mm/day	ACTUAL EVAPOTRANSPIRATION mm/day	DRAINAGE mm/day	SURFACE RUN OFF mm/day	SOIL MOISTURE EXCESS mm	DRYNESS FACTOR	RAINY DAY FACTOR	LENGTH OF DAY FACTOR	POTENTIAL EVAPORATION mm/day	MOISTURE CONTENT mm	SOIL MOISTURE DEFICIT mm	SOIL FIELD CAPACITY mm
1	1	1	0.200	0.095	0.440	0.000	0.000	1.000	0.750	0.028	0.288	109.755	0.245	110.000
2	1	1	9.400	0.067	0.415	0.000	8.673	1.000	0.650	0.449	0.288	118.673	-8.673	110.000
3	1	1	7.400	0.000	3.513	0.000	12.560	1.000	0.550	0.000	0.288	122.560	-12.560	110.000
4	1	1	1.100	0.041	8.914	0.000	4.705	1.000	0.550	0.323	0.288	114.705	-4.705	110.000
5	1	1	0.000	0.000	1.358	0.000	3.347	1.000	1.000	0.000	0.288	113.347	-3.347	110.000
6	1	1	0.000	0.000	0.931	0.000	2.367	1.000	1.000	0.000	0.288	112.367	-2.367	110.000
7	1	1	0.000	0.036	0.775	0.000	1.556	1.000	1.000	0.154	0.288	111.556	-1.556	110.000
8	1	1	1.900	0.112	0.639	0.000	2.705	1.000	0.750	0.646	0.288	112.705	-2.705	110.000
9	1	1	9.000	0.044	0.841	0.000	10.820	1.000	0.650	0.295	0.288	120.820	-10.820	110.000
10	1	1	9.300	0.000	5.875	0.000	14.245	1.000	0.550	0.000	0.288	124.245	-14.245	110.000
11	1	1	0.000	0.003	13.345	0.000	0.896	1.000	1.000	0.013	0.288	110.896	-0.896	110.000
12	1	1	0.300	0.111	0.545	0.000	0.540	1.000	0.750	0.644	0.288	110.540	-0.540	110.000
13	1	1	0.600	0.014	0.501	0.000	0.626	1.000	0.650	0.092	0.288	110.626	-0.626	110.000
14	1	1	0.000	0.088	0.511	0.000	0.027	1.000	1.000	0.381	0.288	110.027	-0.027	110.000
15	1	1	1.700	0.000	0.443	0.000	1.284	1.000	0.750	0.000	0.288	111.284	-1.284	110.000
16	1	1	2.500	0.000	0.598	0.000	3.186	1.000	0.650	0.000	0.288	113.186	-3.186	110.000
17	1	1	0.000	0.151	0.944	0.000	2.091	1.000	1.000	0.657	0.288	112.091	-2.091	110.000
18	1	1	1.500	0.098	0.726	0.000	2.767	1.000	0.750	0.565	0.288	112.767	-2.767	110.000
19	1	1	0.400	0.000	0.854	0.000	2.314	1.000	0.650	0.000	0.288	112.314	-2.314	110.000
20	1	1	0.400	0.000	0.766	0.000	1.948	1.000	0.550	0.000	0.288	111.948	-1.948	110.000
21	1	1	0.900	0.000	0.701	0.000	2.147	1.000	0.550	0.000	0.288	112.147	-2.147	110.000
22	1	1	0.600	0.002	0.736	0.000	2.009	1.000	0.550	0.012	0.288	112.009	-2.009	110.000
23	1	1	4.200	0.000	0.712	0.000	5.498	1.000	0.550	0.000	0.288	115.498	-5.498	110.000
24	1	1	0.000	0.017	1.642	0.000	3.839	1.000	1.000	0.073	0.288	113.839	-3.839	110.000
25	1	1	0.000	0.059	1.103	0.000	2.676	1.000	1.000	0.257	0.288	112.676	-2.676	110.000
26	1	1	0.400	0.002	0.835	0.000	2.239	1.000	0.750	0.012	0.288	112.239	-2.239	110.000
27	1	1	11.200	0.000	0.752	0.000	12.687	1.000	0.650	0.000	0.288	122.687	-12.687	110.000
28	1	1	10.700	0.000	9.189	0.000	14.198	1.000	0.550	0.000	0.288	124.198	-14.198	110.000
29	1	1	1.400	0.000	13.197	0.000	2.401	1.000	0.550	0.000	0.288	112.401	-2.401	110.000
30	1	1	4.800	0.098	0.782	0.000	6.321	1.000	0.550	0.771	0.288	116.321	-6.321	110.000

APPENDIX D8: OUTPUT FROM GRAPH ROUTINE - SOIL MOISTURE GRAPHS



APPENDIX D.9: SUBROUTINE 'GRAPH'

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      SUBROUTINE GRAPH(AIY,AIM,AID,ASMC,CAPT)
C SUBROUTINE TO PLOT SOIL MOISTURE CONTENT FROM SOIL TENSION DATA
C DATA FROM TENSION PROGRAM IS INPUT VIA STREAM FT04.
C OTHER INPUT IS ON FT05 - GRAPH OUTPUT STREAM(I2), CAPTION (40 CH MAX)
C EG 07WINTON SERIES FROM SOIL TENSION DATA
      INTEGER*4 CNT,F81
      LOGICAL LAST
      INTEGER*2 ASTX
      DIMENSION AIY(365),AIM(365),AID(365),ASMC(365),CAPT(10)
      REAL*4 LX,LY
      REAL*4 MNAMES(24),NUMS(12),TEXTX(10),TEXTY(10),XAX(31),YAX(31)
      DATA TEXTY/' ',' ','SOIL',' MOI','STUR','E CO','NTEN','T',' ',' '/
      DATA TEXTX/' ','DAY ',' -',' ',' ',' ',' ','YEAR',' ',' '/
      DATA NUMS/'1','2','3','4','5','6','7','8','9','10','11','12'/
      DATA MNAMES/'JANU','ARY','FEBR','UARY','MARC','H','APRI','L',
     1'MAY',' ','JUNE',' ','JULY',' ','AUGU','ST','SEPT','EMBE',
     2'OCTO','BER','NOVE','MBER','DECE','MBER'/
      DATA SPR,SPB,F81,ASTX/'R',' ','F8.1','*'/
      LAST=.FALSE.
      IY=AIY(1)
      IM=AIM(1)
      ID=AID(1)
      SMC=ASMC(1)
      K=2
C SET UP TEXT FOR X-AXIS
   20 CNT=0
      IMX=(IM-1)*2+1
      TEXTX(6)=SPB
      IF(IM.EQ.9) TEXTX(6)=SPR
      TEXTX(4)=MNAMES(IMX)
      TEXTX(5)=MNAMES(IMX+1)
      TEXTX(10)=NUMS(IY)
C SET UP GRAPH FRAME
      WRITE(6,628)
      CALL GFRAME(32.0,0.0,170.0,50.0,F81,F81,TEXTX,TEXTY)
      WRITE(6,629)
  628 FORMAT( 'GFRAME ENTERD' )
  629 FORMAT( 'GFRAME EXITED' )
      JY=IY
      JM=IM
   40 CNT=CNT+1
      XAX(CNT)=ID*1.0
      YAX(CNT)=SMC
      IY=AIY(K)
      IM=AIM(K)
      ID=AID(K)
      SMC=ASMC(K)
      K=K+1
      IF(K.GT.365) GOTO 300
      IF((JY.EQ.IY).AND.(JM.EQ.IM)) GOTO 40
C SET POINTS INTO GRAPH
      WRITE(6,721)
   60 CALL GPLOT(32.0,0.0,170.0,50.0,XAX,YAX,CNT,ASTX)
      WRITE(6,722)
```

APPENDIX D.9: (CONTINUED)

```
  721 FORMAT( 'GPLOT ENTERD' )
  722 FORMAT( 'GPLOT EXITED' )
C PRINT GRAPH
      WRITE(6,723)
      CALL GPRINT
      WRITE(6,724)
  723 FORMAT( 'GPRINT ENTERD' )
  724 FORMAT( 'GPRINT EXITTED' )
C PRINT CAPTION
      WRITE(11,600)CAPT
C BACK FOR NEXT MONTH
      IF(.NOT. LAST) GOTO 20
      WRITE(11,601)
      RETURN
  300 LAST=.TRUE.
      GOTO 60
  600 FORMAT(1H0,20X,10A4)
  601 FORMAT(1H1,' END OF SOIL MOISTURE CONTENT GRAPHS' )
      END
```

APPENDIX D.10 :ROUTINE 'GRAPHTNS'

```
C ROUTINE TO PLOT SOIL MOISTURE CONTENT FROM SOIL TENSION DATA
C DATA FROM TENSION PROGRAM IS INPUT VIA STREAM FT04.
C OTHER INPUT IS ON FT05 - GRAPH OUTPUT STREAM(I2), CAPTION (40 CH MAX)
C EG 07WINTON SERIES FROM SOIL TENSION DATA
      INTEGER*4 CNT,CAPT(10),F81
      LOGICAL LAST
      INTEGER*2 ASTX
      REAL*4 LX,LY,TEXTX(10),TEXTY(10)
      REAL*4 MNAMES(24),NUMS(12),XAX(31),YAX(31)
      DATA TEXTY/' ',' ','SOIL','MOI','STUR','E CO','NTEN','T',' ',' '/
      DATA TEXTX/' ','DAY ',' -',' ',' ',' ',' ','YEAR',' ',' '/
      DATA NUMS/'1','2','3','4','5','6','7','8','9','10','11','12'/
      DATA MNAMES/'JANU','ARY','FEBR','UARY','MARC','H','APRI','L',
     1'MAY',' ','JUNE',' ','JULY',' ','AUGU','ST','SEPT','EMBE',
     2'OCTO','BER','NOVE','MBER','DECE','MBER'/
      DATA SPR,SPB,F81,ASTX/'R',' ','F8.1','*'/
      LAST=.FALSE.
      READ(5,500)IDEV,CAPT
      READ(4,400,END=300)IY,IM,ID,SMC
C SET UP TEXT FOR X-AXIS
   20 CNT=0
      IMX=(IM-1)*2+1
      TEXTX(6)=SPB
      IF(IM.EQ.9) TEXTX(6)=SPR
      TEXTX(4)=MNAMES(IMX)
      TEXTX(5)=MNAMES(IMX+1)
      TEXTX(10)=NUMS(IY)
C SET UP GRAPH FRAME
      CALL GFRAME(32.0,0.0,300.0,50.0,F81,F81,TEXTX,TEXTY)
      JY=IY
      JM=IM
   40 CNT=CNT+1
      XAX(CNT)=ID*1.0
      YAX(CNT)=SMC
      READ(4,400,END=300)IY,IM,ID,SMC
      IF((JY.EQ.IY).AND.(JM.EQ.IM)) GOTO 40
C SET POINTS INTO GRAPH
   60 CALL GPLOT(32.0,0.0,300.0,50.0,XAX,YAX,CNT,ASTX,IDEV)
C PRINT GRAPH
      CALL GPRINT(IDEV)
C PRINT CAPTION
      WRITE(IDEV,600)CAPT
C BACK FOR NEXT MONTH
      IF(.NOT. LAST) GOTO 20
      WRITE(IDEV,601)
      STOP
  300 LAST=.TRUE.
      GOTO 60
  400 FORMAT(3I3,F9.2)
  500 FORMAT(I2,10A4)
  600 FORMAT(1H0,20X,10A4)
  601 FORMAT(1H1,' END OF SOIL MOISTURE CONTENT GRAPHS')
      END
```

APPENDIX D.11: SUBROUTINE 'GFRAM', 'GPRINT' AND 'GPLOT'

```
C SUBROUTINES TO PRODUCE LINE PRINTER GRAPH PLOTS 1 PER PAGE
C GFRAME SETS UP THE FRAME,HEADINGS AND CO-ORDINATE VALUES
C INPUT PARAMETERS:
C UX,LX,UY,LY - UPPER & LOWER BOUNDS FOR X AND Y CO-ORDINATES
C TYPNX,TYPNY-  FORMAT FOR X & Y VALUES
C TEXTX,TEXTY - HEADING FOR X & Y  MAXIMUM 40 CHARACTERS
      SUBROUTINE GFRAME(UX,LX,UY,LY,TYPNX,TYPNY,TEXTX,TEXTY)
      LOGICAL*1 LG1(40),LGX(4)
      LOGICAL*4 LG4(40),LGX4
      INTEGER*2 FRAME(51,101),PFRAME(51,20),KOUNT(51,101),TEXT2(2),
     1MINUS,PLUS,ALPHAI,SPACE
      INTEGER*4 TX(10),PXFORM,PYFORM,TYPNX,TYPNY,FTEXT(10),
     2TEXTX(10),TEXTY(10),TEXTLY(40),TEXT4
      REAL*4 YVAL(11),XVAL(11),LX,LY
      COMMON/COMGPH/KOUNT,FRAME,PFRAME
      COMMON/COMPAT/XVAL,YVAL,PXFORM,PYFORM,FTEXT
      EQUIVALENCE(LGX4,LGX(1)),(TX(1),LG1(1)),(TEXTLY(1),LG4(1))
      EQUIVALENCE(TEXT4,TEXT2(1))
      DATA SPACE,ALPHAI,MINUS,PLUS/' ','I','-','+'/
C COPY HEADING FOR EQUIVALENCING
      DO 10 I=1,10
      TX(I)=TEXTY(I)
   10 CONTINUE
C CLEAR PLOT AREA AND POSITION COUNT
      DO 30 I=1,51
      DO 20 J=1,101
      KOUNT(I,J)=0
      FRAME(I,J)=SPACE
   20 CONTINUE
   30 CONTINUE
C SET UP FRAME BOUNDARY
      K=0
      DO 50 I=1,51
      FRAME(I,1)=ALPHAI
      FRAME(I,101)=ALPHAI
      IF(K.NE.0) GOTO 40
      FRAME(I,1)=PLUS
      K=5
   40 K=K-1
   50 CONTINUE
      K=0
      DO 60 J=1,101
      FRAME(1,J)=MINUS
      FRAME(51,J)=MINUS
      IF(K.NE.0) GOTO 55
      FRAME(51,J)=PLUS
      K=10
   55 K=K-1
   60 CONTINUE
      FRAME(1,1)=PLUS
      FRAME(51,101)=PLUS
C
C ESTABLISH INTERVAL VALUES
      XVAL(1)=LX
      XVAL(11)=UX
      XRANG=UX-LX
      DO 70 I=1,9
```

APPENDIX D.11: (CONTINUED)

```
      XVAL(I+1)=(XRANG*I)/10+LX
   70 CONTINUE
      YVAL(1)=UY
      YVAL(11)=LY
      YRANG=UY-LY
      K=2
      DO 80 I=1,9
      YVAL(K)=(YRANG*(10-I))/10+LY
      K=K+1
   80 CONTINUE
C
C CLEAR AREA TO LEFT OF THE FRAME
      DO 100 I=1,51
      DO 90 K=1,20
      PFRAME(I,K)=SPACE
   90 CONTINUE
  100 CONTINUE
C
C SET UP Y-AXIS HEADING
      K=5
      DO 120 I=1,40
      LGX(1)=LG1(I)
      LG4(I)=LGX4
      TEXT4=TEXTLY(I)
      PFRAME(K,10)=TEXT2(1)
      K=K+1
  120 CONTINUE
C
C COPY X-AXIS HEADING
      DO 130 I=1,10
      FTEXT(I)=TEXTX(I)
  130 CONTINUE
C
C COPY X AND Y PRINT FORMATS
      PXFORM=TYPNX
      PYFORM=TYPNY
      RETURN
      END
```

APPENDIX D.11: (CONTINUED)

```
C SUBROUTINE TO PRINT LINE PRINTER GRAPH. IDEV IS FILE STREAM.
      SUBROUTINE GPRINT(IDEV)
      REAL*4 XVAL(11),YVAL(11)
      INTEGER*4 PXFORM,PYFORM,PFORM(7),QFORM(7),BLANK,FTEXT(10)
      INTEGER*2 LINE(121),PLINE(101),FIGS(10),AFORM(12),FRAME(51,101),
     1PFRAME(51,20),KOUNT(51,101)
      COMMON/COMGPH/KOUNT,FRAME,PFRAME
      COMMON/COMPAT/XVAL,YVAL,PXFORM,PYFORM,FTEXT
      EQUIVALENCE(LINE(21),PLINE(1))
      DATA PFORM/'(','1H ','6A1,','6A1,','8A1',',101','A1)'/
      DATA BLANK/'8A1'/
      DATA QFORM/'(','1H ','14X,',' 11(','     ',',2X)',')'/
      DATA FIGS/'1','2','3','4','5','6','7','8','9','?'/
C OVERWRITE PLOT CHARACTERS AT MULTIPLE POINTS
      DO 20 I=1,51
      DO 10 J=1,101
      IF(KOUNT(I,J).LE.1) GOTO 10
      K=KOUNT(I,J)
      IF(K.GT.10) K=10
      FRAME(I,J)=FIGS(K)
   10 CONTINUE
   20 CONTINUE
C PRINT 5 BLANK LINES
      WRITE(IDEV,600)
C PRINT FRAME
      K=5
      L=1
      DO 100 I=1,51
      K=K+1
      IF(K.GE.5) GOTO 50
      PFORM(5)=BLANK
C SET UP PRINT LINE
      DO 30 LN=1,20
      LINE(LN)=PFRAME(I,LN)
   30 CONTINUE
      DO 40 LN=1,101
      PLINE(LN)=FRAME(I,LN)
   40 CONTINUE
      WRITE(IDEV,PFORM)LINE
      GOTO 100
   50 K=0
      DO 60 M=1,12
   60 AFORM(M)=PFRAME(I,M)
      PFORM(5)=PYFORM
C SET UP PRINT LINE
      DO 70 LN=1,101
      PLINE(LN)=FRAME(I,LN)
   70 CONTINUE
      WRITE(IDEV,PFORM)AFORM,YVAL(L),(FRAME(I,NN),NN=1,101)
      L=L+1
  100 CONTINUE
C WRITE X-AXIS VALUES
      QFORM(5)=PXFORM
      WRITE(IDEV,QFORM)XVAL
C WRITE X-AXIS HEADING
      WRITE(IDEV,601)FTEXT
      RETURN
  600 FORMAT(1H1,5(/))
  601 FORMAT(1H0,/30X,10A4)
      END
```

APPENDIX D.11: (CONTINUED)

```
C SUBROUTINE TO INSERT POINTS INTO GRAPH FRAME
C  UX,LX,UY,LY  ARE UPPER AND LOWER GRAPH BOUNDS
C  XVALS IS VECTOR OF X VALUES, YVALS THE VECTOR OF YVALUES
C  NVAL IS THE VECTOR LENGTH.CHAR THE REQUIRED PLOTTING SYMBOL



      SUBROUTINE GPLOT(UX,LX,UY,LY,XVALS,YVALS,NVAL,CHAR,IDEV)
      REAL*4 LX,LY
      DIMENSION XVALS(NVAL),YVALS(NVAL)
      INTEGER*2 KOUNT(51,101),FRAME(51,101),CHAR
      COMMON/COMGPH/KOUNT,FRAME
C CALCULATE VALUE OF EACH PRINT POSITION
      XINT=(UX-LX)/100.0
      YINT=(UY-LY)/50.0
C CALCULATE PLOT POSITION OF VALUES
      DO 50 I=1,NVAL
      IF((XVALS(I).LT.LX).OR.(XVALS(I).GT.UX)) GOTO 40
      IF((YVALS(I).LT.LY).OR.(YVALS(I).GT.UY)) GOTO 40
      IX=INT((XVALS(I)-LX)/XINT+0.5)+1
      IY=51-INT((YVALS(I)-LY)/YINT+0.5)
C INSERT CHARACTER & INCREASE COUNT
      FRAME(IY,IX)=CHAR
      KOUNT(IY,IX)=KOUNT(IY,IX)+1
      GOTO 50
C WRITE VALUES OUTSIDE PLOT RANGE
   40 WRITE(IDEV,600)XVALS(I),YVALS(I),CHAR
   50 CONTINUE
      RETURN
  600 FORMAT(1H1,' POINT ',2F10.4,',SYMBOL ',A1,', LIES OUTSIDE FRAME')
      END
```

APPENDIX E

W.D.P.P.

APPENDIX E.1: WORKDAY PROBABILITY PREDICTION PROGRAM FOR TILLAGE OPERATION

```
C       WORKDAY PROBABILITY PREDICTION PROGRAM   (WDPP)
C
C
C             EAST OF SCOTLAND COLLEGE OF AGRICULCURE
C
C THIS PROGRAMME PREDICTS THE NUMBER OF DAYS AVAILABLE FOR SOIL WORKS
C AT A GIVEN SOIL WORKABILITY CRITERION AND PROBABILITY LEVELAND  SOIL
C MOISTURE CONTENTS FOR EVERY DAY OF THE YEAR  FOR TEN YEARS.
C TABLES CONTAINING NUMBERS OF AVAILABLE DAYS IN EACH MONTH AND
C THE WEEK OF THE YEAR AND PROBABILITIES OF A DAY BEING WORKDAY
 C OR NON-WORKDAY CAN BE OBTAINED FROM CHANNEL 6
C GRAPHS OF SOIL MOISTURE AGAINST DAYS OF THE MONTH CAN BE OBTAIND
C FROM CHANNEL 11
C A TABLE OF NUMERICAL RESULTS COULD BE OBTAIND FROMCHANNEL 4
C DAILY HOURS OF SUNSHINE AND PRECIPITATION ARE READ FROM
CHANNEL 9
C VARIABLE NAMES
C     PE   =MONTHLY POTENTIAL EVAPORATION
C     MNTH =LENGTH OF MONTH IN DAYS
C     DPE  =DAILY POTENTIAL EVAPORATION
C     LDCF =LENGTH OF DAY CORRECTION FACTOR
C     DS   =DURATION OF SUNSHINE
C     RDCF =RAINY DAY CORRECTION FACTOR
C     TM   =TEMPERATURE
C     PPT  =PRECIPITATION
C     DL   =DAYLENGTH
C     DLIND =INDEX FOR DL
C     NDS  =NO. OF SUCCESIVE RAINY DAYS
C     PTAB&PPTFAC ARE USED TO DETERMINE RUN-OFF ALLOWANCE
C     WD   =WORK DAY ,SET TO N FOR NONE WORK DAY,SET TO W FOR WORK DAY
C     DM   =DRAINAGE AT SATURATION MM/DAY
C     DF   =DRAINAGE AT FIELD CAPACITY MM/DAY
C     MM   =MOISTURE CONTENT AT SATURATION MM IN A GIVEN DEPTH
C     FCAP =SOIL MOISTURE CONTENT AT FIELD CAPACITY
C     WDT  =ARRAY GIVING NO. OF WORKDAYS
C          BY THE DAY OF THE YEAR
C     WDTP =THE PROBABILITY ASSOCIATED WITH WDT
      DIMENSION PTAB(3),PPTFAC(3),RFAC(3),AIY(365)
      DIMENSION AIM(365),AID(365),ASMC(365)
      DIMENSION DL(24,36),PPT(31,12,10),DS(31,12,10),DPE(12,10)
      INTEGER*4 MAPRBT,MIPRBT,DPRBT,NSTEP
      INTEGER*4 IDENT(20),MNTH(12),DLIND(24),SCOND,DN,PSTEP
      INTEGER*4 TABLE(11,12,11),IXY(31),TST(11),P,T
      INTEGER*4 WDTP(366),WDTAB(11,52,11),DNUM,WDT(366)
      REAL*4 NP,LDCF,MM,CAPT(10),ICOL(11),MACRTN,MICRTN,INCRTN,CRTN
      INTEGER*2 WD(31,12,10),LINE(32),SPACE2,WORK,NONWK
      INTEGER*2 LINE1(31),LINE2(31),LINE3(31),LINE4(31),TWD(31,12)
      LOGICAL FRUNOF
      COMMON/WEATHR/ DL,PPT,DS,MNTH,DLIND,DPE
      DATA IXY/1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,
     118,19,20,21,22,23,24,25,26,27,28,29,30,31/
      DATA RFAC/0.75,0.65,0.55/
      DATA LAST,WORK,NONWK,SPACE2/'LAST','W','N','  '/
      DATA PTAB,PPTFAC/0,25.4,50.8,1,0.75,0.5/
```

```
     APPENDIX E.1: (CONTINUED)
C  C CLEAR PROBABILITY TABLE
      DO 15 I=1,11
      DO 10 J=1,12
      DO 5 K=1,11
      TABLE(I,J,K)=0
    5 CONTINUE
   10 CONTINUE
   15 CONTINUE
C    CLEAR WORKDAY LIST
      DO 18 I=1,366
      WDT(I)=0
   18 CONTINUE
      DO 71 I=1,11
      DO 72 J=1,52
      DO 73 K=1,11
      WDTAB(I,J,K)=0
   73 CONTINUE
   72 CONTINUE
   71 CONTINUE
C READ IN VALUES FROM TABLES VIA SOBROUTINS
      CALL THORNS
      WRITE(3,999)
  999 FORMAT(1H ,' THORNS ENDED')
      CALL DAYLNG
      WRITE(3,998)
  998 FORMAT(1H ,' DAYLNG ENDED')
      CALL CLIMAT
C READ IN THE LATITUDES , FIELD CAPACITY AND CAPTION
      READ(5,921)CAPT
  921 FORMAT(10A4)
      READ(5,500)LAT,FCAP
C CHECK THAT THE LATITUDE IS HELD IN THE INDEX
      DO 20 I=1,24
      IF(LAT.EQ.DLIND(I)) GOTO 25
   20 CONTINUE
C LATITUDE WAS NOT FOUND SO TERMINATE PROGRAM
      WRITE(3,604)LAT,DLIND
      STOP
C SET LATITUDE INDEX
   25 LINX=I
C INPUT DRAINAGE COEFFICIONTS
   30 READ(5,502,END=490)IDENT,DM,DF,MM,BD,NY
      IF(IDENT(1).EQ.LAST)  STOP
C READ INITIAL WORKDAY CRITERION
      READ(5,503)MAPRBT,MIPRBT,DPRBT,MACRTN,MICRTN,INCRTN
      READ(5,504)AGF,TAB,WTAB,MTAB,LTAB
      COEFF1=(ALOG(DM/DF))/(MM-FCAP)
      COEFF2=(ALOG(DM)-(MM*COEFF1))
      PSTEP=(MAPRBT-MIPRBT)/DPRBT
      JXY=0
      NSTEP=(MACRTN-MICRTN)/INCRTN
      CRTN=MICRTN
      DO 420 IC=1,NSTEP
      CRTN=CRTN+INCRTN
      JXY=JXY+1
```

APPENDIX E.1: (CONTINUED)

```
      ICOL(JXY)=CRTN
C SET INITIAL VALUES
      IF(TAB.LT.0) GOTO 8
      IF(IC.GT.1)GO TO 8
      WRITE(4,445)IDENT
  445 FORMAT(1H1,20A4/
     1'   DATE      DPT      ET   DRAIN   RUNOFF   SMEX     ',
     1'  DRY   RDCF   LDCF    DPE      SMC      SMD     FCAP')
C CLEAR DAILY TOTALS
    8 DO 35J=1,12
      DO 32I=1,31
      TWD(I,J)=0
   32 CONTINUE
   35 CONTINUE
      SMEX=0.0
      NDS=0
      SMD=0
      DRY=1.0
      RDCF=0.6
      LDCF=0.5
C NOW CALCULATE TO DETERMINE WORKDAY,IY IS YEAR IDEX,IM IS MONTH INDEX
C DAY NO. IS DNUM
      DO 300 IY=1,NY
      DNUM=0
      K=1
      SMD=0
      SMCP=FCAP
      DO 280 IM=1,12
C ESTABLISH NO OF DAYS IN CURRENT MONTH
      IN=MNTH(IM)
      DO 260 ID=1,IN
      DNUM=DNUM+1
      DRAIN=EXP((COEFF1*SMCP+COEFF2)*2.30259)
  501 FORMAT(2F8.4)
      IF(DRAIN.GT.30) DRAIN=30
C CALCULATE LENGTH OF DAY FACTOR,LDCF
C FIND WHICH THIRD OF THE MPNTH THE DAY IS IN
      I3=ID/10+1
      IF(I3.GT.3) I3=3
C NOW FIND THE DAY LENGTH FOR THIS LATITUDE FROM THE SMITHSOWIAN TABLE
C IF THE POSITION IN THE TABLE FOR THIS LATITUDE(LINX)
      IP=(IM-1)*3+I3
C NO OF POSSIBLE HOURS OF SUNSHINE (NP)
      NP=DL(LINX,IP)
C NOW LOOK UP THE ACTUAL AMOUNT OF SUNSHINE FOR THIS DAY,DSHN
      DSHN=DS(ID,IM,IY)
      LDCF=DSHN/NP
C SET TO 1 FOR JUNE-AUGUST INCLUSIVE
      IF((IM.EQ.6).OR.(IM.EQ.7).OR.(IM.EQ.8)) LDCF=1
C NOW DETERMINE THE RAINY DAY CORRECTION FACTOR RDCF
C LOOK UP PRECIPITATION FROM TABLE
      DPT=PPT(ID,IM,IY)
      RDCF=1
      IF(DPT.LT.0.0001) GOTO 40
C INCREMENT NO. OF SUCCESIVE RAINY DAYS
      NDS=NDS+1
```

APPENDIX E.1: (CONTINUED)

```
      IF(NDS.GT.3) NDS=3
      RDCF=RFAC(NDS)
      GOTO 45
   40 NDS=0
C NOW CALCULATE RUN OFF
   45 RUNOFF=0.0
      IF(FCAP.LT.50.0) GOTO 50
      BD=1.41
      A=SMCP/(BD*300.0)
      B=A-0.18
      SS=B*BD*1500.0
      Q1=(DPT-(DPT*(615.0356-2.847*SS))/(DPT+529.437-2.437*SS))*0
      Q2=(DPT-(DPT*(219.6338-0.904*SS))/(DPT+134.0358-0.494*SS))*0
      IF(Q1.LT.0) Q1=0
      IF(Q2.LT.0) Q2=0
      IF((SS.LT.198.1).AND.(SS.GT.0.0)) RUNOFF=Q1
      IF(SS.GE.198.1) RUNOFF=Q2
C NOW CALCULATE DRYNESS FACTOR,DAILY EVAPOTRANSPIRATION,& SOIL MOISTURE
C DEFICIENCY
   50 ET=DPE(IM,IY)*DRY*RDCF*LDCF*0.10
      SMC=DPT+SMCP-ET-DRAIN-RUNOFF
      IF(SMC.GT.MM) SMC=MM
      IF(SMC.LT.0) SMC=0.0
      SMD=FCAP-SMC
      SMEX=0.0
      IF(SMD.LT.0.0) SMEX=SMD*(-1.0)
      AIY(K)=IY
      AIM(K)=IM
      AID(K)=ID
      ASMC(K)=SMC
      K=K+1
      IF(TAB.LT.0) GOTO 9
      IF(IC.GT.1)GO TO 9
      WRITE(4,444)ID,IM,IY,DPT,ET,DRAIN,RUNOFF,SMEX,
     1DRY,RDCF,LDCF,DPE(IM,IY),SMC,SMD,FCAP
  444 FORMAT(1H ,3I3,12F8.3)
C SET UP DRYNESS FACTOR FOR NEXT DAYS VALUES
    9 DRY=1
      IF(SMD.GT.2.0*20.4) DRY=0.0
      IF(SMD.GT.5.8*25.4)DRY=0.00
      IF(SMD.GT.8.4*25.4) DRY=0.0
C WAS IT A WORK DAY
      WD(ID,IM,IY)=NONWK
      TEST=CRTN*FCAP
      IF(SMC.LT.TEST)WD(ID,IM,IY)=WORK
C FORM TOTAL NO OF WORKDAYS FOR THIS PARTICULAR MONTH AND DAY OF THE YEAR
      IF(WD(ID,IM,IY).EQ.WORK) TWD(ID,IM)=TWD(ID,IM)+1
   41 IF(WD(ID,IM,IY).EQ.WORK) WDT(DNUM)=WDT(DNUM)+1
      SMCP=SMC
  260 CONTINUE
  280 CONTINUE
      IF(AGF.LT.0) GOTO 300
      IF(IC.GT.1)GO TO 300
      WRITE(3,626)
      CALL GRAPH(AIY,AIM,AID,ASMC,CAPT)
```

APPENDIX E.1: (CONTINUED)

```
      WRITE(3,627)
  626 FORMAT(' GRAPH ENTERD')
  627 FORMAT(' GRAPH EXIT')
  300 CONTINUE
C CHECK LIST FOR WORKDAYS ON DAILY BASIS
      DO 310 J=1,365
      WDTP(J)=AINT((WDT(J)*1.0/NY*100.0)+0.5)
  310 CONTINUE
  432 FORMAT(1H,I4,2I8)
C NOW WRITE OUT WORKDAY RESULTS IN TABULAR FORM
      DO 400 J=1,12
      IF(WTAB.LT.0) GOTO 13
      WRITE(6,600)LAT,SCOND,FCAP,J,CRTN
      WRITE(6,601)IXY
   13 DO 340 K=1,NY
      DO 320 I=1,32
  320 LINE(I)=SPACE2
      I2=MNTH(J)
      L=2
      LINE(1)=K
      DO 330 I=1,I2
      LINE(L)=WD(I,J,K)
  330 L=L+1
      IF(WTAB.LT.0) GOTO 340
      WRITE(6,602)LINE
  340 CONTINUE
C WRITE TOTALS AND PROBABILITIES
C NO OF YEARS GIVES MAX. POSSIBLE WORKDAYS FOR EACH DAY
C SUBTRACTION WILL GIVE NON-WORKDAYS
C LINE 1 IS TOTAL WORKDAYS
C LINE 2 IS TOTAL NON-WORKDAYS
C LINE 3 P-W.D
C LINE 4 P-NW.D
      DO 350 I=1,31
      LINE1(I)=TWD(I,J)
      LINE2(I)=NY-TWD(I,J)
      LINE3(I)=AINT((LINE1(I)*1.0/NY*100.0)+0.5)
      LINE4(I)=AINT((LINE2(I)*1.0/NY*100.0)+0.5)
  350 CONTINUE
C   PRINT THE LINES
      IF(WTAB.LT.0) GOTO 14
      WRITE(6,606)LINE1
      WRITE(6,607)LINE2
      WRITE(6,608)LINE3
      WRITE(6,609)LINE4
   14 T=100
      DO 360 P=1,PSTEP
      TST(P)=T
      T=T-DPRBT
  360 CONTINUE
      DO 380 P=1,PSTEP
      DO 370 IJ=1,31
      IF(LINE3(IJ).GE.TST(P)) TABLE(IC,J,P)=TABLE(IC,J,P)+1
  370 CONTINUE
  380 CONTINUE
```

APPENDIX E.1: (CONTINUED)

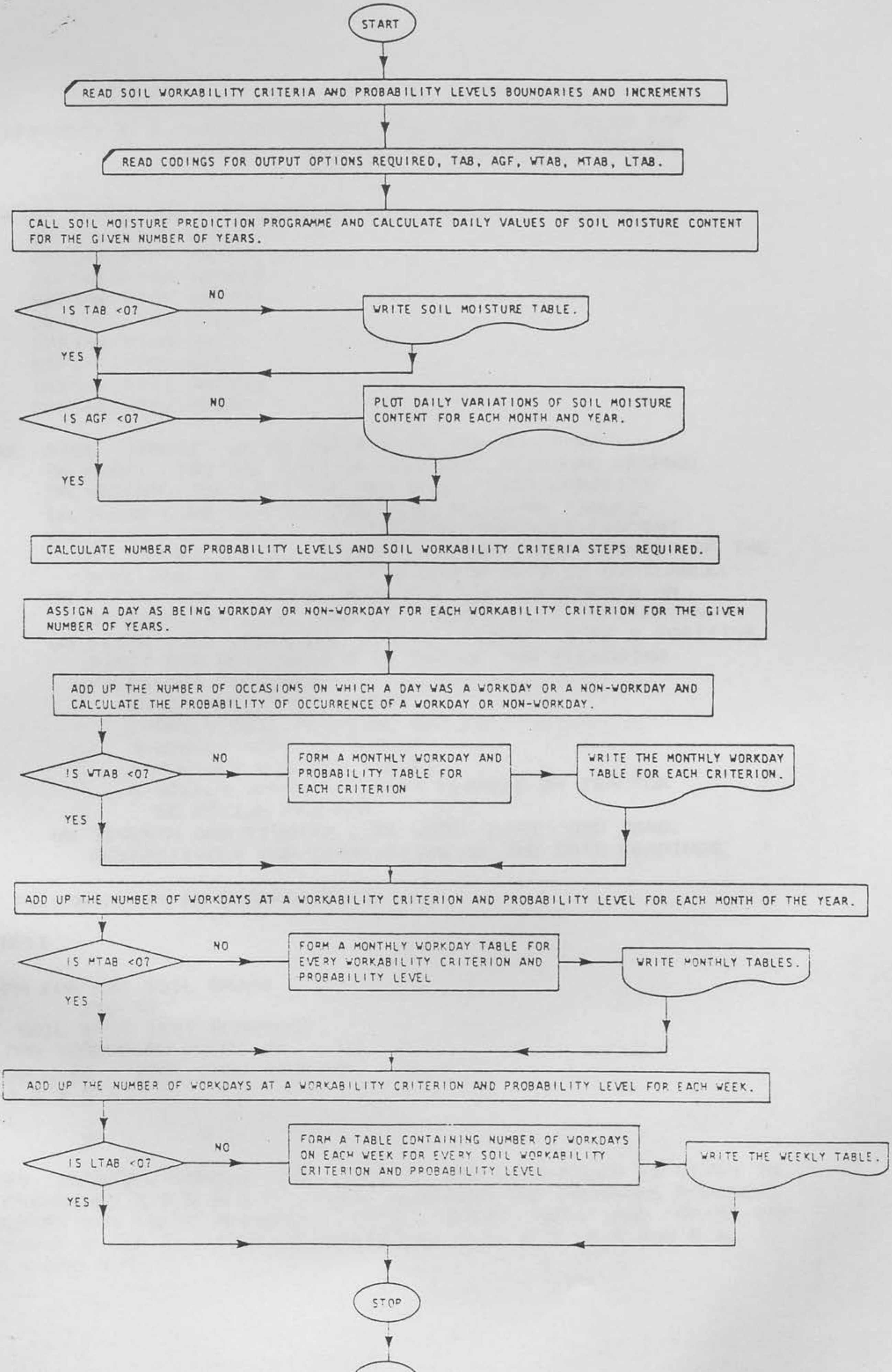
```
  400 CONTINUE
C DAY NO. BY START OF THE WEEK
  401 SDN=1
      DO 415 IW=1,52
      DO 410 P=1,PSTEP
      DN=SDN
      DO 405 J=1,7
      IF(TST(P).LT.WDTP(DN)) WDTAB(IC,IW,P)=WDTAB(IC,IW,P)+1
      DN=DN+1
  405 CONTINUE
  410 CONTINUE
C DAY NO AT START OF NEXT WEEK
      SDN=SDN+7
  415 CONTINUE
  420 CONTINUE
      IF(MTAB.LT.0) GO TO 17
      DO 440 J=1,12
      WRITE(6,610)J
      WRITE(6,611)(ICOL(I),I=1,NSTEP)
      DO 430 K=1,PSTEP
      WRITE(6,612)TST(K),(TABLE(L,J,K),L=1,NSTEP)
  430 CONTINUE
  440 CONTINUE
      WRITE(6,614)
C WEEKLY TABLE
   17 IF(LTAB.LT.0)GOTO 16
      DO 460 J=1,52
      WRITE(6,613) J
      WRITE(6,611)(ICOL(I),I=1,NSTEP)
      DO 450 K=1,PSTEP
      WRITE(6,612)TST(K),(WDTAB(L,J,K),L=1,NSTEP)
  450 CONTINUE
  460 CONTINUE
CX    16 DO 451 K=1,PSTEP
CX       WRITE(12,617)TST(K)
CX   451 CONTINUE
   16 WRITE(12,616)(ICOL(I),I=1,NSTEP)
      DO 470 J=1,52
      DO 469 K=1,PSTEP
      WRITE(12,618)(WDTAB(L,J,K),L=1,NSTEP)
  469 CONTINUE
  470 CONTINUE
      GOTO 30
  490 STOP
  500 FORMAT(I3,4X,F8.2)
  502 FORMAT(20A4/,F5.2,F8.4,F8.2,F8.4,I2)
  503 FORMAT(3I5,3F5.2)
  504 FORMAT(6F2.0)
  600 FORMAT(1H1,' RESULTS FOR LATITUDE:',I3,'N.',A4,' SOIL CONDITION,'
     1,F8.2,' FIELD CAP.'/,' MONTH NO: ',I3,'CRITERION: ',F6.2/' YEAR !
     1',30X,'DAY NUMBER' )
  601 FORMAT(1H ,5X,31I3)
  602 FORMAT(1H ,I4,' !',31(1X,A2))
  604 FORMAT(1H ,' LATITUDE SPECIFIED: ',I4,' NOT IN INDEX: '/1H ,24I3)
```

APPENDIX E.1 (CONTINUED)

```
605 FORMAT(1H ,' SOIL CONDITION : ',A4,' NOT LEGAL TYPE' )
606 FORMAT(1H0,100('-')//' T.WD  ',31I3)
607 FORMAT(1H,'T.NWD ',31I3)
608 FORMAT(1H,'% WD  ',31I3)
609 FORMAT(1H,'% NWD ',31I3)
610 FORMAT(1H1,' MONTH NO: ',I3)
611 FORMAT(1H0,20X,11F4.2)
612 FORMAT(1H,16X,12I4)
613 FORMAT(1H0,/'WEEK NO: ',I6)
614 FORMAT(1H1,' WEEKLY TABLE')
616 FORMAT(11F5.2)
617 FORMAT(12I4)
618 FORMAT(12I4)
    END
```

ALL SUBROUTINES USED IN THIS PROGRAM ARE SIMMILAR TO THOSE USED BY SOIL MOISTURE PROGRAM WHICH IS GIVEN INAPPENDIX D.1

APPENDIX E.2: FLOW CHART OF THE WORKDAY PROBABILITY PREDICTION PROGRAM (WDPP)



APPENDIX E.3: RUNNING INSTRUCTIONS AND DATA FILES FOR WORKDAY PROBABILITY PREDICTION PROGRAM (WDPP)

DEFINE INPUT AND OUTPUT FILES AS FOLLOWS:

```
DEFINE(FT05,INPUT1);
DEFINE(FT07,INPUT2);
DEFINE(FT08,INPUT3);
DEFINE(FT09,INPUT4);
DEFINE(FT03,OUT1);
DEFINE(FT04,OUT2);
DEFINE(FT06,OUT3);
DEFINE(FT11,OUT4);
DEFINE(FT12,OUT5).
```

WHERE: FILE 'INPUT1' IS AN INPUT FILE AND CONTAINS:
- ON FIRST LINE THE CAPTION FOR SOIL MOISTURE GRAPHS;
- ON SECOND LINE LATITUDE AND SOIL FIELD CAPACITY;
- ON THIRD LINE HEADING FOR SOIL MOISTURE TABLES;
- ON FOURTH LINE DRAINAGE AND SOIL MOISTURE CONTENT AT SATURATION AND FIELD CAPACITY, BULK DENSITY OF THE SOIL AND NO. OF YEARS FOR WHICH DATA IS AVAILABLE;
- ON FIFTH LINE MAXIMUM, MINIMUM, AND INCREMENTS ON PROBABILITY LEVEL AND SOIL WORKABILITY CRITERION;
- ON SIXTH LINE CODES FOR OUTPUT OPTIONS. TYPE A POSITIVE DIGIT FOR OPTIONS 1-5 IF ANY OF THE FOLLOWING FILES ARE REQUIRED:
  - 1-SOIL MOISTURE GRAPHS
  - 2-DAILY SOIL MOISTURE TABLES
  - 3-WEEKLY WORKDAY TABLES
  - 4-MONTHLY WORKDAY TABLES
  - 5-WEEKLY WORKDAY TABLES READBLE BY TRACTOR SELECTION PROGRAM
- ON SEVENTH AND EIGHTTH LINE WORD 'LAST' AND ZERO, RESPECTIVELY FOR TERMINATION OF THE DATA READINGS.

THE FOLLOWING IS AN EXAMPLE FILE.

EXAMPLE:

```
GRAPH FOR MAC SOIL GRASS
 56      110.00
MAC SOIL 1978 TEST RUNGRASS_
26.700.700000145.00001.29     02
  100   80   1001.2000.9000.05
 1 2 3 4 5 6
LAST
 0        0        0
```

FILES 'INPUT2','INPUT3' AND 'INPUT4' ARE DATA FILES AS GIVEN IN APPENDICES D.6,D.4,D.5; 'OUT1' CONTAINS THE PROGRAMS PROGRESS REPORT AND ERROR MESSAGES, 'OUT2','OUT3','OUT4' AND 'OUT5' ARE OUTPUT FILES AS GIVEN IN APPENDICES D.7; E.4, E.5 AND E.6; D.8 AND H.9

APPENDIX E.4: OUTPUT FROM WORKDAY PREDICTION PROGRAMME - DAILY TABLE

RESULTS FOR LATITUDE: 56^0N. SOIL CONDITION. 104.00 FIELD CAP.

MONTH NO: 9 CRITERION: 1 05

DAY NUMBER

YEAR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	W	W	W	W	W	W	W	W	W	W	N	N	N	N	W	W	N	N	N	N	N	N	W	N	W	W	N	N	N	N
2	W	N	N	N	W	N	N	N	W	N	W	W	W	N	W	W	W	W	W	W	W	W	W	W	W	W	N	N	N	N
3	N	N	N	W	W	W	W	W	W	W	W	W	W	N	N	N	W	W	W	W	W	W	W	W	W	W	N	N	N	N
4	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W
5	W	W	W	W	W	W	N	W	N	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	N	W	N	N	W	W
6	N	N	N	N	W	W	N	N	W	W	W	N	N	N	N	N	N	W	W	N	N	N	N	W	N	N	W	W	W	W
7	W	W	W	W	W	W	N	W	N	N	N	N	N	W	W	N	N	W	W	W	W	W	N	N	W	W	N	W	W	W
8	W	W	W	W	N	W	W	W	W	W	N	N	W	W	W	W	W	W	W	W	W	N	N	W	W	W	N	N	W	N
9	W	W	W	W	N	N	W	N	N	N	N	N	W	N	W	W	N	W	W	W	W	W	W	W	W	N	N	W	W	N
10	N	N	N	N	W	W	N	N	N	W	W	W	W	N	N	N	W	W	W	W	W	W	W	W	N	N	N	N	N	N
T.WD	7	6	6	7	8	8	5	6	7	7	6	5	7	6	7	6	7	9	9	8	8	7	7	8	7	7	2	4	5	4
T.NWD	3	4	4	3	2	2	5	4	3	3	4	5	3	4	3	4	3	1	1	2	2	3	3	2	3	3	8	6	5	6
% WD	70	60	60	70	80	80	50	60	70	70	60	50	70	60	70	60	70	90	90	80	80	70	70	80	70	70	20	40	50	40
% NWD	30	40	40	30	20	20	50	40	30	30	40	50	30	40	30	40	30	10	10	20	20	30	30	20	30	30	80	60	50	60

T.WD = No. of occasions on which the soil was workable.

T.NWD = No. of occasions on which the soil was unworkable.

% WD = Percentage of years on which the day was a work day

% NWD = Percentage of years on which the day was non-work day.

APPENDIX E.5: OUTPUT FROM WORKDAY PREDICTION PROGRAM - MONTHLY TABLE

MONTH NUMBER 1

PROBABILITY LEVEL %	SOIL WORKABILITY CRITERION % of F.C.				
	95	1 00	1 05	1 10	1 15
100	0	0	4	16	26
90	0	0	5	27	30
80	0	0	14	30	31
70	0	2	24	31	31
60	0	2	28	31	31
50	0	3	31	31	31
40	0	4	31	31	31
30	0	6	31	31	31
20	0	21	31	31	31
10	5	29	31	31	31
0	31	31	31	31	31

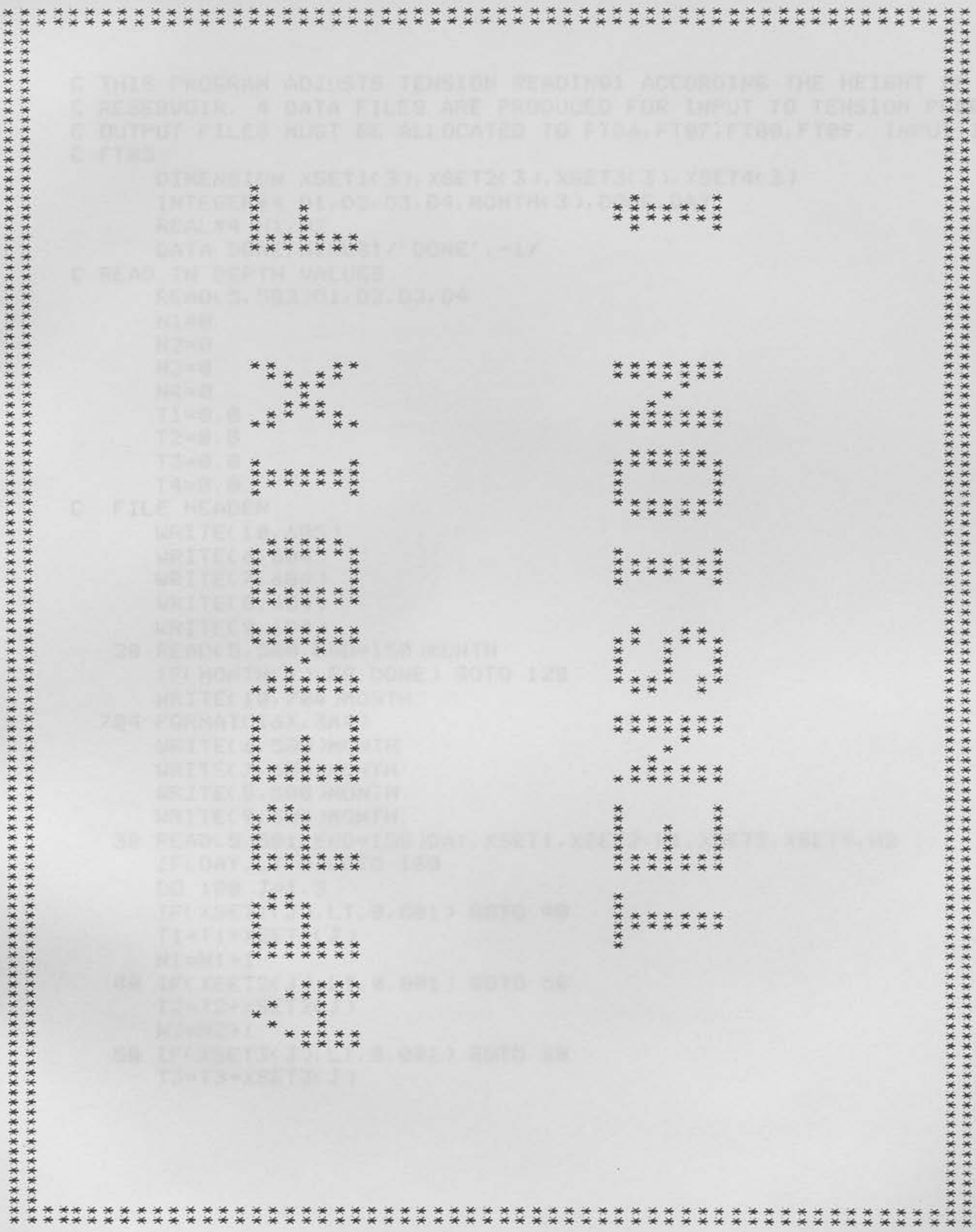
APPENDIX E.6: OUTPUT FROM WORKDAY PREDICTION PROGRAM - WEEKLY TABLE

PROBABILITY LEVEL 100%

WEEK NUMBER	SOIL WORKABILITY CRITERION		
	1 00	1.05	1 10
1	0	5	7
2	0	0	7
3	0	0	7
4	0	0	7
5	0	2	7
6	0	2	7
7	0	2	7
8	2	7	7
9	1	7	7
10	3	7	7

PROBABILITY LEVEL 90%

WEEK NUMBER	SOIL WORKABILITY CRITERION		
	1 00	1 05	1 10
1	0	7	7
2	0	2	7
3	0	4	7
4	0	1	7
5	0	4	7
6	0	4	7
7	0	3	7
8	1	7	7
9	0	7	7
10	2	7	7



APPENDIX F.1: SOIL MOISTURE TENSION PROGRAM 1

```
C THIS PROGRAM ADJUSTS TENSION READING1 ACCORDING THE HEIGHT OF MERCURY
C RESERVOIR. 4 DATA FILES ARE PRODUCED FOR INPUT TO TENSION PROGRAM.
C OUTPUT FILES MUST BE ALLOCATED TO FT06,FT07,FT08,FT09. INPUT IS FROM
C FT05
      DIMENSION XSET1(3),XSET2(3),XSET3(3),XSET4(3)
      INTEGER*4 D1,D2,D3,D4,MONTH(3),DONE,DAY
      REAL*4 H1,H2
      DATA DONE,MINUS1/'DONE',-1/
C READ IN DEPTH VALUES
      READ(5,502)D1,D2,D3,D4
      N1=0
      N2=0
      N3=0
      N4=0
      T1=0.0
      T2=0.0
      T3=0.0
      T4=0.0
C  FILE HEADER
      WRITE(10,605)
      WRITE(6,604)
      WRITE(7,604)
      WRITE(8,604)
      WRITE(9,604)
   20 READ(5,500,END=150)MONTH
      IF(MONTH(1).EQ.DONE) GOTO 120
      WRITE(10,704)MONTH
  704 FORMAT(16X,3A4)
      WRITE(6,500)MONTH
      WRITE(7,500)MONTH
      WRITE(8,500)MONTH
      WRITE(9,500)MONTH
   30 READ(5,501,END=150)DAY,XSET1,XSET2,H1,XSET3,XSET4,H2
      IF(DAY.LT.0)GOTO 180
      DO 100 J=1,3
      IF(XSET1(J).LT.0.001) GOTO 40
      T1=T1+XSET1(J)
      N1=N1+1
   40 IF(XSET2(J).LT.0.001) GOTO 50
      T2=T2+XSET2(J)
      N2=N2+1
   50 IF(XSET3(J).LT.0.001) GOTO 60
      T3=T3+XSET3(J)
```

APPENDIX F.1: (CONTINUED)

```
      N3=N3+1
   60 IF(XSET4(J).LT.0.001) GOTO 100
      T4=T4+XSET4(J)
      N4=N4+1
  100 CONTINUE
C CLACULATE MEANS
      RM1=T1/N1
      RM2=T2/N2
      RM3=T3/N3
      RM4=T4/N4
C CALCULATE TENSION VALUES
      TN1=(12.6*RM1-13.6*H1-D1)*(0.0009807)
      TN2=(12.6*RM2-13.6*H1-D2)*(0.0009807)
      TN3=(12.6*RM3-13.6*H2-D3)*(0.0009807)
      TN4=(12.6*RM4-13.6*H2-D4)*(0.0009807)
      IF(TN1.LT.0.0000001) TN1=.001
      IF(TN2.LT.0.0000001) TN2=.001
      IF(TN3.LT.0.0000001) TN3=.001
      IF(TN4.LT.0.0000001) TN4=.001
C 4 FILES FOR OUTPUT
      WRITE(6,600)DAY,TN1
      WRITE(7,600)DAY,TN2
      WRITE(8,600)DAY,TN3
      WRITE(9,600)DAY,TN4
      WRITE(10,700)DAY,TN1,TN2,TN3,TN4
      T1=0.0
      T2=0.0
      T3=0.0
      T4=0.0
      N1=0
      N2=0
      N3=0
      N4=0
      GOTO 30
C END OF MONTH
 180  WRITE(6,601)MINUS1
      WRITE(7,601)MINUS1
      WRITE(8,601)MINUS1
      WRITE(9,601)MINUS1
      GOTO 20
C END OF RUN
  120 WRITE(6,602)
      WRITE(10,701)
  701 FORMAT(1H1,20X,'APPENDIX F.4: (CONTINUED)')
      STOP
  150 WRITE(6,603)
      STOP
C FORMATS
```

APPENDIX F.1: (CONTINUED)

```
      500 FORMAT(3A4)
      501 FORMAT(I2,2(6F5.1,F3.1))
      502 FORMAT(4I4)
      600 FORMAT(I2,F5.3,73X)
      601 FORMAT(I2,78X)
      602 FORMAT(' END OF RUN ')
      603 FORMAT(' OUT OF DATA ')
      604 FORMAT(' GENERATED FILE ')
      700 FORMAT(16X,I4,4F10.4)
      605 FORMAT(1H1,//,20X,'APPENDIX F.4: OUTPUT FROM TENSION PROGRAM 1
     1',/,20X,'SOIL MOISTURE TENSION (BAR) FOR MACMERRY SOIL',//,
     116X,'DATE',10X,'GRASS',13X,'BARE  SOIL',/,24X,'-----------------
     1-----------------',/,24X,'200 MM     400 MM     200 MM     400 MM'
     1,/,24X,'******     ******     ******     ******')
          END
```

APPENDIX F.2: RUNNING INSTRUCTIONS AND INPUT FILES FOR TENSION PROGRAM 1 (TENSION1)

DEFINE INPUT AND OUTPUT FILES AS FOLLOWS:

```
DEFINE(FT05,INPUT);
DEFINE(FT06,OUT1);
DEFINE(FT07,OUT2);
DEFINE(FT08,OUT3);
DEFINE(FT09,OUT4);
DEFINE(FT10,OUT5).
```

WHERE: FILE 'INPUT' IS THE INPUT FILE IN THE FORM OF APPENDICES C.1 AND C.2 ; 'OUT1','OUT2','OUT3' AND'OUT4' ARE OUTPUT FILES FOR EACH DEPTH AND SURFACE COVER IN THE FOLLOWING FORM WHICH IS READABLE BY TENSION PROGRAM 2 AND CONTAINS ,HEADING, MONTH NAME AND DATE AND TENSION VALUE FOR THAT DATE IN TERMS OF MILI-BAR, ON EACH LINE.

EXAMPLE:

```
 GENERATED FILE 1
JANUARY
01002
02007
03004
04015
.
.
.
.
31026
-1
FEBRUARY
```

AND FINALLY, 'OUT5' IS AN OUTPUT FILE FOR OBSERVATION SIMILAR TO APPENDICES F.3 AND F.4.

APPENDIX F.3: OUTPUT FROM TENSION PROGRAM 1
SOIL MOISTURE TENSION (BAR) FOR WINTON SOIL

DATE	GRASS		BARE SOIL	
	200 MM	400 MM	200 MM	400 MM
	******	******	******	******
JANUARY				
FEBRUARY				
MARCH				
6	0.0532	0.0056	0.0315	0.1210
13	0.0454	0.0010	0.0344	0.0934
15	0.0326	0.0010	0.0364	0.0020
20	0.0264	0.0010	0.0245	0.0010
21	0.0336	0.0025	0.0371	0.0071
28	0.0281	0.0010	0.0282	0.0004
29	0.0297	0.0052	0.0175	0.0010
30	0.0230	0.0010	0.0241	0.0010
31	0.0416	0.0199	0.0303	0.0010
APRIL				
3	0.0362	0.0010	0.0361	0.0010
4	0.0410	0.0053	0.0361	0.0033
6	0.0484	0.0172	0.0468	0.0140
7	0.0480	0.0255	0.0530	0.0145
10	0.1061	0.0264	0.0526	0.0400
11	0.0757	0.0251	0.0464	0.0285
12	0.0542	0.0321	0.0621	0.0173
13	0.0592	0.0379	0.0575	0.0157
14	0.0571	0.0210	0.0629	0.0010
15	0.0518	0.0181	0.0625	0.0010
16	0.0505	0.0218	0.0497	0.0042
17	0.0533	0.0110	0.0476	0.0234
18	0.0492	0.0250	0.0472	0.0012
19	0.0513	0.0346	0.0492	0.0094
21	0.0567	0.0466	0.0504	0.0201
22	0.0464	0.0499	0.0397	0.0247
23	0.0468	0.0808	0.0393	0.0304
24	0.0476	0.0424	0.0484	0.0010
25	0.0497	0.0729	0.0601	0.0327
26	0.0730	0.0387	0.0490	0.0739
27	0.0633	0.0503	0.0495	0.0719
28	0.0324	0.0010	0.0331	0.0010

APPENDIX F.3: (CONTINUED)

MAY				
3	0.0423	0.0041	0.0270	0.0010
4	0.0411	0.0074	0.0389	0.0010
5	0.0415	0.0010	0.0990	0.0506
6	0.0472	0.0010	0.0364	0.0010
7	0.0464	0.0070	0.1002	0.0650
8	0.0443	0.0066	0.0415	0.0033
9	0.0456	0.0132	0.0462	0.0118
10	0.0505	0.0161	0.0458	0.0204
11	0.0451	0.0246	0.0513	0.0176
12	0.0438	0.0325	0.0512	0.0200
13	0.0537	0.0226	0.0480	0.0386
14	0.0575	0.0243	0.0480	0.0477
15	0.0519	0.0578	0.0531	0.0224
16	0.0523	0.0631	0.0491	0.0217
17	0.0490	0.0813	0.0528	0.0229
18	0.0540	0.0933	0.0469	0.0228
19	0.0582	0.1284	0.1147	0.0893
20	0.0628	0.1482	0.0507	0.0282
22	0.0724	0.1690	0.0631	0.0369
23	0.0733	0.2015	0.0582	0.0352
24	0.0650	0.1764	0.0429	0.0011
25	0.0579	0.1915	0.0404	0.0031
26	0.0630	0.2279	0.0446	0.0044
27	0.0687	0.2608	0.0491	0.0114
28	0.0712	0.2921	0.0524	0.0105
29	0.0766	0.3041	0.0450	0.0147
30	0.0879	0.3566	0.0483	0.0159
31	0.0996	0.4177	0.0528	0.0212
JUNE				
1	0.1087	0.4462	0.0513	0.0267
2	0.1322	0.4796	0.0521	0.0320
3	0.1636	0.5127	0.0525	0.0353
4	0.1856	0.5313	0.0571	0.0387
5	0.2071	0.5569	0.0592	0.0449
6	0.2359	0.7373	0.0641	0.0507
7	0.2629	0.4260	0.0872	0.0585
9	0.3507	0.7281	0.0551	0.0758
10	0.4059	0.7318	0.0555	0.0808
11	0.6093	0.7442	0.0608	0.0886
12	0.6623	0.5253	0.0662	0.0939
13	0.7336	0.3898	0.0425	0.0987
14	0.7731	0.5361	0.0466	0.1114
15	0.7947	0.3779	0.0532	0.1205
16	0.8168	0.7370	0.0539	0.1311
19	0.5775	0.7744	0.0544	0.1609
20	0.8124	0.4299	0.0296	0.0010
21	0.8279	0.6580	0.0430	0.0010
22	0.8198	0.4252	0.0317	0.0010
26	0.5515	0.3935	0.0354	0.0010
27	0.4332	0.4202	0.0376	0.0010
28	0.4433	0.4385	0.0334	0.0010
29	0.4681	0.4592	0.0381	0.0010
30	0.4841	0.4814	0.0410	0.0010

APPENDIX F.3: (CONTINUED)

JULY				
3	0.4871	0.4770	0.0393	0.0010
4	0.4796	0.1857	0.0268	0.0010
6	0.3482	0.0172	0.0305	0.0010
7	0.3597	0.0200	0.0329	0.0010
10	0.3694	0.0878	0.0391	0.0010
11	0.3710	0.1096	0.0441	0.0034
12	0.3806	0.1303	0.0383	0.0010
13	0.3765	0.1670	0.0383	0.0026
14	0.3663	0.2185	0.0506	0.0135
17	0.3034	0.4218	0.0428	0.0553
18	0.2767	0.4902	0.0475	0.0662
20	0.6136	0.5833	0.0504	0.0817
21	0.6235	0.6072	0.0363	0.0896
24	0.6867	0.6577	0.0475	0.1082
25	0.6495	0.6698	0.0489	0.1248
27	0.7811	0.5975	0.0579	0.0803
28	0.8379	0.5815	0.0542	0.0795
AUGUST				
2	0.6528	0.6604	0.0450	0.1036
3	0.7002	0.0384	0.0730	0.0365
25	0.5153	0.3597	0.0433	0.0212
29	0.7640	0.4915	0.0380	0.0377
SEPTEMBER				
7	0.7353	0.4846	0.0358	0.0071
8	0.7335	0.4725	0.0404	0.0114
15	0.7096	0.1801	0.0353	0.0120
19	0.5500	0.0646	0.0404	0.0258
25	0.5605	0.1620	0.0425	0.0497
29	0.5543	0.0010	0.0259	0.0047
OCTOBER				
2	0.5590	0.0085	0.0317	0.0080
4	0.5450	0.0146	0.0396	0.0130
5	0.5238	0.0173	0.0357	0.0169
9	0.4810	0.0523	0.0390	0.0260
10	0.4822	0.0610	0.0495	0.0307
17	0.4459	0.1079	0.0441	0.0302
23	0.4418	0.1590	0.0417	0.0427
24	0.4400	0.1810	0.0379	0.0335
26	0.3786	0.2016	0.0433	0.0361
31	0.4050	0.2317	0.0404	0.0336
NOVEMBER				
1	0.4078	0.1052	0.0347	0.0023
21	0.0175	0.0010	0.0300	0.0010
16	0.0242	0.0010	0.0280	0.0010
DECEMBER				
5	0.0488	0.0012	0.0275	0.0010
11	0.0145	0.0010	0.0064	0.0010
22	0.0230	0.0010	0.0803	0.0718

APPENDIX F.4: OUTPUT FROM TENSION PROGRAM 1
SOIL MOISTURE TENSION (BAR) FOR MACMERRY SOIL

DATE	GRASS		BARE SOIL	
	200 MM	400 MM	200 MM	400 MM
	******	******	******	******
JANUARY				
FEBRUARY				
MARCH				
6	0.0460	0.0124	0.0477	0.0231
13	0.0485	0.0010	0.0316	0.0009
15	0.0431	0.0013	0.0329	0.0054
20	0.0382	0.0010	0.0361	0.0010
21	0.0457	0.0043	0.0418	0.0057
28	0.0393	0.0010	0.0379	0.0010
29	0.0382	0.0010	0.0367	0.0010
30	0.0420	0.0010	0.0374	0.0010
31	0.0478	0.0005	0.0489	0.0141
APRIL				
3	0.0460	0.0010	0.0507	0.0010
4	0.0457	0.0038	0.0507	0.0043
6	0.0489	0.0128	0.0522	0.0128
7	0.0477	0.0116	0.0530	0.0268
10	0.0580	0.0157	0.0734	0.0468
11	0.0440	0.0235	0.0606	0.0452
12	0.0440	0.0182	0.0598	0.0414
13	0.0485	0.0210	0.0660	0.0402
14	0.0493	0.0010	0.0585	0.0010
15	0.0456	0.0058	0.0663	0.0203
16	0.0478	0.0191	0.0589	0.0203
17	0.0473	0.0137	0.0593	0.0298
18	0.0465	0.0100	0.0581	0.0261
19	0.0436	0.0117	0.0564	0.0364
21	0.0448	0.0210	0.0594	0.0480
22	0.0473	0.0248	0.0611	0.0484
23	0.0456	0.0297	0.0615	0.0509
24	0.0489	0.0326	0.0644	0.0534
25	0.0515	0.0648	0.0631	0.0579
26	0.0494	0.0710	0.0630	0.0533
27	0.0448	0.0165	0.0209	0.0010
28	0.0374	0.0010	0.0374	0.0010

APPENDIX F.4: (CONTINUED)

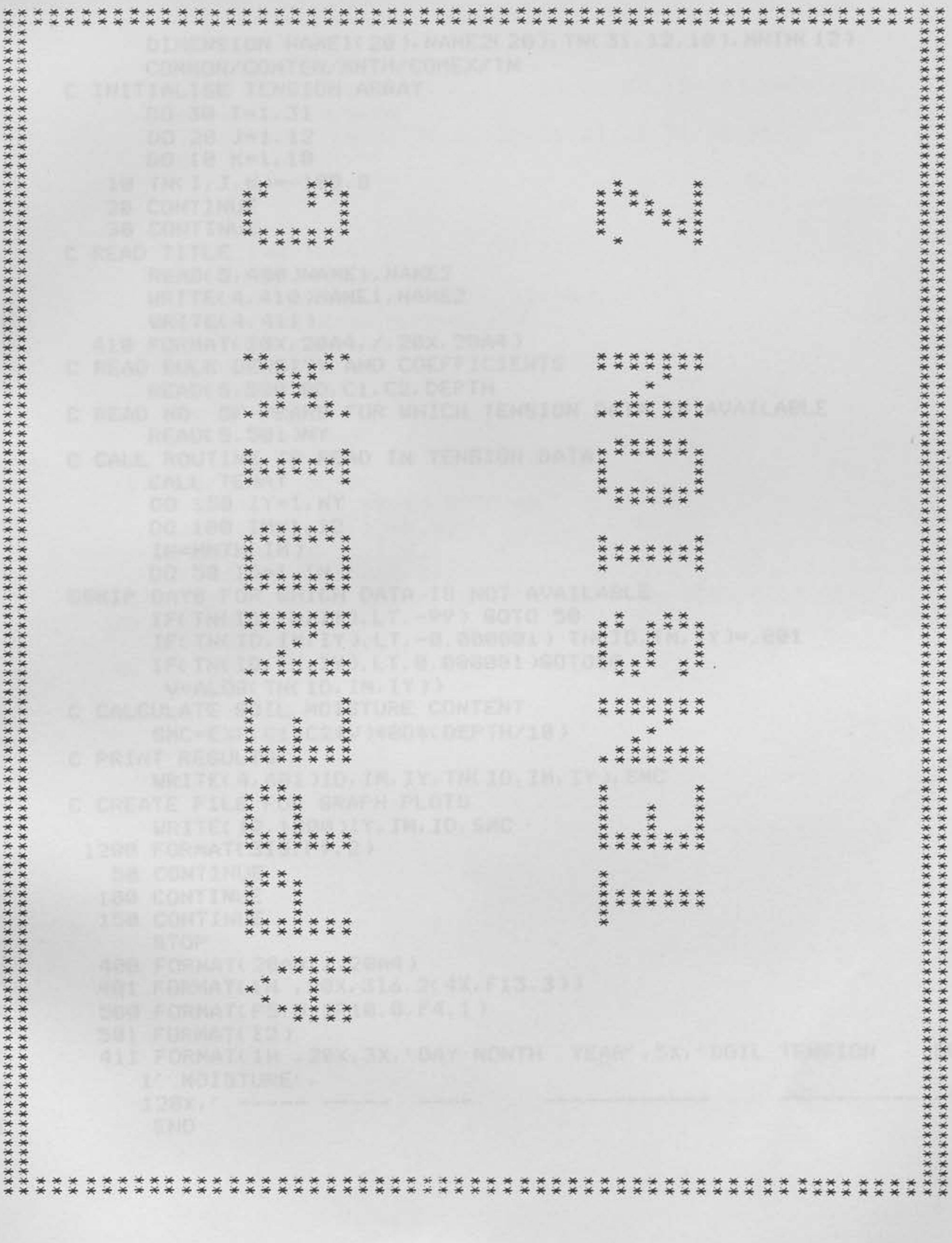
MAY				
3	0.0423	0.0190	0.0494	0.0175
4	0.0411	0.0169	0.0511	0.0224
5	0.0390	0.0010	0.0482	0.0010
6	0.0427	0.0010	0.0519	0.0010
7	0.0441	0.0104	0.0515	0.0100
8	0.0432	0.0121	0.0507	0.0142
9	0.0465	0.0203	0.0536	0.0246
10	0.0428	0.0319	0.0536	0.0283
11	0.0408	0.0343	0.0553	0.0336
12	0.0457	0.0446	0.0565	0.0336
13	0.0465	0.0496	0.0565	0.0377
14	0.0461	0.0553	0.0578	0.0381
15	0.0461	0.0586	0.0606	0.0394
16	0.0436	0.0603	0.0581	0.0438
17	0.0453	0.0800	0.0573	0.0496
18	0.0441	0.0825	0.0560	0.0541
19	0.0445	0.1076	0.0606	0.0629
20	0.0461	0.1171	0.0606	0.0682
22	0.0371	0.1382	0.0649	0.0766
23	0.0359	0.1473	0.0645	0.0617
24	0.0635	0.0896	0.0603	0.0078
25	0.0681	0.1008	0.0509	0.0156
26	0.0665	0.1272	0.0447	0.0300
27	0.0673	0.1560	0.0462	0.0353
28	0.0678	0.1808	0.0446	0.0410
29	0.0703	0.2068	0.0482	0.0446
30	0.0707	0.2500	0.0495	0.0530
31	0.0666	0.3201	0.0606	0.0686
JUNE				
1	0.0709	0.3590	0.0661	0.0737
2	0.0720	0.4264	0.0633	0.0882
3	0.0728	0.4832	0.0633	0.0940
4	0.0783	0.5081	0.0584	0.0989
5	0.0850	0.5465	0.0654	0.1067
6	0.0870	0.5662	0.0687	0.1191
7	0.0883	0.5927	0.0707	0.1273
9	0.0985	0.6788	0.0674	0.1487
10	0.1125	0.6510	0.0592	0.0717
11	0.1409	0.6844	0.0618	0.1608
12	0.1500	0.6980	0.0609	0.1702
13	0.1707	0.5267	0.0599	0.0910
14	0.2498	0.5597	0.0537	0.1824
15	0.2248	0.6187	0.0601	0.1950
16	0.2375	0.5602	0.0626	0.2020
19	0.3218	0.6383	0.0630	0.2164
20	0.2607	0.6319	0.0585	0.2135
21	0.2786	0.7125	0.0589	0.2304
22	0.1897	0.1915	0.0414	0.0010
26	0.1827	0.1849	0.0385	0.0049
27	0.1914	0.2365	0.0501	0.0160
28	0.2022	0.2641	0.0548	0.0216
29	0.2504	0.2868	0.0577	0.0253
30	0.2580	0.3179	0.0601	0.0282

APPENDIX F.4: (CONTINUED)

JULY				
3	0.1880	0.2948	0.0518	0.0207
4	0.1806	0.0482	0.0406	0.0010
6	0.1477	0.0127	0.0468	0.0123
7	0.1535	0.0219	0.0494	0.0212
10	0.1635	0.0924	0.0494	0.0368
11	0.1649	0.1111	0.0498	0.0442
12	0.0920	0.1268	0.0493	0.0466
13	0.1071	0.1624	0.0514	0.0540
14	0.1111	0.1957	0.0511	0.0615
17	0.1349	0.3570	0.0552	0.0768
18	0.1432	0.4202	0.0566	0.0993
20	0.1685	0.5089	0.0587	0.1083
21	0.1722	0.5291	0.0612	0.1054
24	0.1902	0.5887	0.0636	0.1140
25	0.2063	0.5998	0.0632	0.1132
27	0.2093	0.6123	0.0631	0.0806
28	0.2229	0.6168	0.0627	0.0715
AUGUST				
2	0.2577	0.6187	0.0633	0.0738
3	0.2565	0.3378	0.0642	0.0021
25	0.2639	0.2051	0.0448	0.0264
29	0.3273	0.2665	0.0410	0.0469
SEPTEMBER				
7	0.2350	0.1795	0.0418	0.0033
8	0.2333	0.0555	0.0443	0.0098
15	0.1428	0.0091	0.0357	0.0095
19	0.1218	0.0499	0.0415	0.0330
25	0.0423	0.0577	0.1059	0.1122
29	0.0819	0.0025	0.0410	0.0010
OCTOBER				
2	0.0407	0.0099	0.0432	0.0104
4	0.0519	0.0236	0.0473	0.0178
5	0.0485	0.0223	0.0481	0.0211
6	0.0489	0.0330	0.0471	0.0233
9	0.0560	0.0521	0.0502	0.0318
10	0.0596	0.0520	0.0517	0.0325
12	0.0626	0.0871	0.0516	0.0332
13	0.0631	0.0707	0.0538	0.0358
17	0.0670	0.0631	0.0558	0.0296
18	0.0743	0.0749	0.0563	0.0334
23	0.0698	0.0914	0.0554	0.0506
24	0.0690	0.1038	0.0575	0.0502
26	0.0769	0.1076	0.0562	0.0259
31	0.0772	0.1013	0.0562	0.0004

APPENDIX F.4: (CONTINUED)

NOVEMBER				
1	0,0818	0.0010	0,0274	0.0010
9	0,0874	0.0200	0.0518	0,0211
10	0,0845	0,0246	0.0518	0,0248
13	0,0835	0.0010	0.0478	0.0010
15	0,0391	0.0020	0.0406	0,0010
21	0.0411	0,0062	0,0374	0,0013
22	0.0473	0.0120	0,0397	0.0010
DECEMER				
1	0,0536	0,0143	0,1608	0.1412
11	0,0449	0.0053	0,0584	0,0013
22	0,0387	0,0010	0,1439	0,1326



APPENDIX G.1: SOIL MOISTURE TENSION PROGRAM 2

```
      DIMENSION NAME1( 20 ),NAME2( 20 ),TN( 31, 12, 10 ),MNTH( 12 )
      COMMON/COMTEN/MNTH/COMEX/TN
C INITIALISE TENSION ARRAY
      DO 30 I=1,31
      DO 20 J=1,12
      DO 10 K=1,10
   10 TN( I, J, K )=-100.0
   20 CONTINUE
   30 CONTINUE
C READ TITLE
      READ( 5, 400 )NAME1, NAME2
      WRITE( 4, 410 )NAME1, NAME2
      WRITE( 4, 411 )
  410 FORMAT( 20X, 20A4, /, 20X, 20A4 )
C READ BULK DENSITY AND COEFFICIENTS
      READ( 5, 500 )BD, C1, C2, DEPTH
C READ NO. OF YEARS FOR WHICH TENSION DATA IS AVAILABLE
      READ( 5, 501 )NY
C CALL ROUTINE TO READ IN TENSION DATA
      CALL TENAT
      DO 150 IY=1, NY
      DO 100 IM=1, 12
      IN=MNTH( IM )
      DO 50 ID=1, IN
CSKIP DAYS FOR WHICH DATA IS NOT AVAILABLE
      IF( TN( ID, IM, IY ).LT.-99 ) GOTO 50
      IF( TN( ID, IM, IY ).LT.-0.000001 ) TN( ID, IM, IY )=.001
      IF( TN( ID, IM, IY ).LT.0.000001 )GOTO50
       V=ALOG( TN( ID, IM, IY ))
C CALCULATE SOIL MOISTURE CONTENT
      SMC=EXP( C1+C2*V )*BD*( DEPTH/10 )
C PRINT RESULTS
      WRITE( 4, 401 )ID, IM, IY, TN( ID, IM, IY ), SMC
C CREATE FILE FOR GRAPH PLOTS
      WRITE( 12, 1200 )IY, IM, ID, SMC
 1200 FORMAT( 3I3, F9.2 )
   50 CONTINUE
  100 CONTINUE
  150 CONTINUE
      STOP
  400 FORMAT( 20A4, /, 20A4 )
  401 FORMAT( 1H , 20X, 3I6, 2( 4X, F13.3 ))
  500 FORMAT( F5.0, 2F10.0, F4.1 )
  501 FORMAT( I2 )
  411 FORMAT( 1H , 20X, 3X, 'DAY MONTH  YEAR', 5X, 'SOIL TENSION    SOIL',
     1' MOISTURE',
     120X,' ----- -----  ----     ------------     ------------' )
      END
```

APPENDIX 6.1: (CONTINUED)

```
      BLOCK DATA
      INTEGER*4 MNTH(12),DLIND(24)
      REAL*4 DL(24,36),PPT(31,12,10),DS(31,12,10),DPE(12,10)
      COMMON/COMTEN/MNTH
      DATA MNTH/31,28,31,30,31,30,31,31,30,31,30,31/
      END


      SUBROUTINE TENAT
      INTEGER*4 MNTH(12)
      DIMENSION SCARD(11),TN(31,12,10)
      COMMON/COMTEN/MNTH/COMEX/TN
      DATA IMP/'IM'/
      READ(9,900)ICARD
      DO 40 M=1,12
C READ MONTH NAME
      READ(9,902)MNAME
C READ IN 1 MONTHS VALUES IN DAY ORDER
   10 READ(9,901)SCARD
      IF(SCARD(1).LT.00.0) GOTO 40
      IDAY=INT(SCARD(1)+0.5)
      DO 20 J=1,10
      TN(IDAY,M,J)=SCARD(J+1)
C WRITE OUT VALUE TO CHECK TENSION HAS BEEN CORRECTLY READ
   20 CONTINUE
      GOTO 10
   40 CONTINUE
      RETURN
  900 FORMAT(4A4)
  901 FORMAT(F2.0,10F5.3,28X)
  902 FORMAT(A4)
      END
```

APPENDIX 6.2: SOIL MOISTURE TENSION(BAR) AND SOIL MOISTURE CONTENT (MM) FOR MACMERRY GRASS AT PLOUGH LAYER (300 MM)

DAY	MONTH	YEAR	SOIL TENSION	SOIL MOISTURE
6	3	1	0.046	112.910
13	3	1	0.048	112.447
15	3	1	0.043	113.647
20	3	1	0.038	115.011
21	3	1	0.046	112.910
28	3	1	0.039	114.723
29	3	1	0.038	115.011
30	3	1	0.042	113.905
31	3	1	0.048	112.447
3	4	1	0.046	112.910
4	4	1	0.046	112.910
6	4	1	0.049	112.223
7	4	1	0.048	112.447
10	4	1	0.058	110.412
11	4	1	0.044	113.395
12	4	1	0.044	113.395
13	4	1	0.048	112.447
14	4	1	0.049	112.223
15	4	1	0.046	112.910
16	4	1	0.048	112.447
17	4	1	0.047	112.675
18	4	1	0.047	112.675
19	4	1	0.044	113.395
21	4	1	0.045	113.149
22	4	1	0.047	112.675
23	4	1	0.046	112.910
24	4	1	0.049	112.223
25	4	1	0.051	111.791
26	4	1	0.049	112.223
27	4	1	0.045	113.149
28	4	1	0.037	115.307

APPENDIX 6.2 : (CONTINUED)

3	5	1	0.042	113.905
4	5	1	0.041	114.170
5	5	1	0.039	114.723
6	5	1	0.043	113.647
7	5	1	0.044	113.395
8	5	1	0.043	113.647
9	5	1	0.047	112.675
10	5	1	0.043	113.647
11	5	1	0.041	114.170
12	5	1	0.046	112.910
13	5	1	0.047	112.675
14	5	1	0.046	112.910
15	5	1	0.046	112.910
16	5	1	0.044	113.395
17	5	1	0.045	113.149
18	5	1	0.044	113.395
19	5	1	0.044	113.395
20	5	1	0.046	112.910
22	5	1	0.037	115.307
23	5	1	0.036	115.612
24	5	1	0.064	109.368
25	5	1	0.068	108.730
26	5	1	0.066	109.044
27	5	1	0.067	108.886
28	5	1	0.068	108.730
29	5	1	0.070	108.426
30	5	1	0.071	108.278
31	5	1	0.067	108.886
1	6	1	0.071	108.278
2	6	1	0.072	108.132
3	6	1	0.073	107.988
4	6	1	0.078	107.300
5	6	1	0.085	106.414
6	6	1	0.087	106.175
7	6	1	0.088	106.058
9	6	1	0.099	104.860
10	6	1	0.113	103.530
11	6	1	0.141	101.341
12	6	1	0.150	100.738
13	6	1	0.171	99.473
14	6	1	0.250	95.893
15	6	1	0.225	96.873
16	6	1	0.238	96.349
19	6	1	0.322	93.579
20	6	1	0.261	95.495
21	6	1	0.279	94.883
22	6	1	0.190	98.466
26	6	1	0.183	98.823
27	6	1	0.191	98.416
28	6	1	0.202	97.886
29	6	1	0.250	95.893
30	6	1	0.258	95.602

APPENDIX G.2 : (CONTINUED)

3	7	1	0.188	98.567
4	7	1	0.181	98.928
6	7	1	0.148	100.869
7	7	1	0.154	100.483
10	7	1	0.164	99.874
11	7	1	0.165	99.816
12	7	1	0.092	105.604
13	7	1	0.107	104.076
14	7	1	0.111	103.708
17	7	1	0.135	101.768
18	7	1	0.143	101.204
20	7	1	0.169	99.585
21	7	1	0.172	99.417
24	7	1	0.190	98.466
25	7	1	0.206	97.701
27	7	1	0.209	97.565
28	7	1	0.223	96.956
2	8	1	0.258	95.602
3	8	1	0.256	95.674
25	8	1	0.264	95.390
29	8	1	0.327	93.440
7	9	1	0.235	96.467
8	9	1	0.233	96.547
15	9	1	0.143	101.204
19	9	1	0.122	102.767
25	9	1	0.042	113.905
29	9	1	0.082	106.783
2	10	1	0.041	114.170
4	10	1	0.052	111.582
5	10	1	0.049	112.223
6	10	1	0.049	112.223
9	10	1	0.056	110.786
10	10	1	0.060	110.051
12	10	1	0.063	109.534
13	10	1	0.063	109.534
17	10	1	0.067	108.886
18	10	1	0.074	107.847
23	10	1	0.070	108.426
24	10	1	0.069	108.577
26	10	1	0.077	107.434
31	10	1	0.077	107.434
1	11	1	0.082	106.783
9	11	1	0.087	106.175
10	11	1	0.085	106.414
13	11	1	0.084	106.535
15	11	1	0.038	115.011
21	11	1	0.041	114.170
22	11	1	0.047	112.675
1	12	1	0.054	111.176
11	12	1	0.045	113.149
22	12	1	0.039	114.723

APPENDIX G.3: SOIL MOISTURE TENSION(BAR) AND SOIL MOISTURE CONTENT (MM) FOR MACMERRY GRASS SUBSOIL (600 MM)

DAY	MONTH	YEAR	SOIL TENSION	SOIL MOISTURE
6	3	1	0.012	154.808
13	3	1	0.001	251.011
15	3	1	0.001	251.011
20	3	1	0.001	251.011
21	3	1	0.004	191.687
28	3	1	0.001	251.011
29	3	1	0.001	251.011
30	3	1	0.001	251.011
31	3	1	0.001	251.011
3	4	1	0.001	251.011
4	4	1	0.004	191.687
6	4	1	0.013	152.416
7	4	1	0.012	154.808
10	4	1	0.016	146.384
11	4	1	0.024	135.283
12	4	1	0.018	143.068
13	4	1	0.021	138.842
14	4	1	0.001	251.011
15	4	1	0.006	177.151
16	4	1	0.019	141.572
17	4	1	0.014	150.235
18	4	1	0.010	160.396
19	4	1	0.012	154.808
21	4	1	0.021	138.842
22	4	1	0.025	134.213
23	4	1	0.030	129.537
24	4	1	0.033	127.158
25	4	1	0.065	111.450
26	4	1	0.071	109.553
27	4	1	0.017	144.668
28	4	1	0.001	251.011

APPENDIX 6.3 : (CONTINUED)

3	5	1	0.019	141.572
4	5	1	0.017	144.668
5	5	1	0.001	251.011
6	5	1	0.001	251.011
7	5	1	0.010	160.396
8	5	1	0.012	154.808
9	5	1	0.020	140.166
10	5	1	0.032	127.921
11	5	1	0.034	126.422
12	5	1	0.045	119.714
13	5	1	0.050	117.285
14	5	1	0.055	115.131
15	5	1	0.059	113.570
16	5	1	0.060	113.199
17	5	1	0.080	107.039
18	5	1	0.083	106.276
19	5	1	0.108	100.970
20	5	1	0.117	99.410
22	5	1	0.138	96.269
23	5	1	0.147	95.094
24	5	1	0.090	104.615
25	5	1	0.101	102.295
26	5	1	0.127	97.837
27	5	1	0.156	94.001
28	5	1	0.181	91.322
29	5	1	0.207	88.969
30	5	1	0.250	85.762
31	5	1	0.320	81.741
1	6	1	0.359	79.933
2	6	1	0.426	77.317
3	6	1	0.483	75.451
4	6	1	0.508	74.714
5	6	1	0.546	73.673
6	6	1	0.566	73.160
7	6	1	0.583	72.740
9	6	1	0.679	70.615
10	6	1	0.651	71.195
11	6	1	0.684	70.514
12	6	1	0.698	70.237
13	6	1	0.527	74.183
14	6	1	0.560	73.311
15	6	1	0.619	71.897
16	6	1	0.560	73.311
19	6	1	0.638	71.475
20	6	1	0.632	71.607
21	6	1	0.712	69.966
22	6	1	0.191	90.372
26	6	1	0.185	90.935
27	6	1	0.236	86.729
28	6	1	0.264	84.858
29	6	1	0.287	83.490
30	6	1	0.318	81.841

APPENDIX 6.3 : (CONTINUED)

3	7	1	0.295	83.045
4	7	1	0.048	118.220
6	7	1	0.013	152.416
7	7	1	0.022	137.592
10	7	1	0.092	104.169
11	7	1	0.111	100.433
12	7	1	0.127	97.837
13	7	1	0.162	93.313
14	7	1	0.196	89.919
17	7	1	0.357	80.020
18	7	1	0.420	77.530
20	7	1	0.509	74.686
21	7	1	0.529	74.128
24	7	1	0.589	72.595
25	7	1	0.600	72.334
27	7	1	0.612	72.056
28	7	1	0.617	71.942
2	8	1	0.619	71.897
3	8	1	0.338	80.876
25	8	1	0.205	89.137
29	8	1	0.267	84.672
7	9	1	0.180	91.420
8	9	1	0.056	114.728
15	9	1	0.009	163.717
19	9	1	0.050	117.285
25	9	1	0.058	113.948
29	9	1	0.003	202.719
2	10	1	0.010	160.396
4	10	1	0.024	135.283
5	10	1	0.022	137.592
6	10	1	0.033	127.158
9	10	1	0.052	116.394
10	10	1	0.052	116.394
12	10	1	0.087	105.307
13	10	1	0.071	109.553
17	10	1	0.063	112.130
18	10	1	0.075	108.391
23	10	1	0.091	104.390
24	10	1	0.104	101.714
26	10	1	0.108	100.970
31	10	1	0.101	102.295
1	11	1	0.001	251.011
9	11	1	0.020	140.166
10	11	1	0.025	134.213
13	11	1	0.001	251.011
15	11	1	0.002	219.353
21	11	1	0.006	177.151
22	11	1	0.012	154.808
1	12	1	0.014	150.235
11	12	1	0.005	183.546
22	12	1	0.001	251.011

APPENDIX 6.4: SOIL MOISTURE TENSION(BAR) AND SOIL MOISTURE CONTENT (MM) FOR MACMERRY SOIL AT PLOUGH LAYER (300 MM)

DAY	MONTH	YEAR	SOIL TENSION	SOIL MOISTURE
6	3	1	0.048	112.447
13	3	1	0.032	116.934
15	3	1	0.033	116.587
20	3	1	0.036	115.612
21	3	1	0.042	113.905
28	3	1	0.038	115.011
29	3	1	0.037	115.307
30	3	1	0.037	115.307
31	3	1	0.049	112.223
3	4	1	0.051	111.791
4	4	1	0.051	111.791
6	4	1	0.052	111.582
7	4	1	0.053	111.377
10	4	1	0.073	107.988
11	4	1	0.061	109.876
12	4	1	0.060	110.051
13	4	1	0.066	109.044
14	4	1	0.058	110.412
15	4	1	0.066	109.044
16	4	1	0.059	110.230
17	4	1	0.059	110.230
18	4	1	0.058	110.412
19	4	1	0.056	110.786
21	4	1	0.059	110.230
22	4	1	0.061	109.876
23	4	1	0.061	109.876
24	4	1	0.064	109.368
25	4	1	0.063	109.534
26	4	1	0.063	109.534
27	4	1	0.021	121.785
28	4	1	0.037	115.307

APPENDIX 6.4 : (CONTINUED)

3	5	1	0.049	112.223
4	5	1	0.051	111.791
5	5	1	0.048	112.447
6	5	1	0.052	111.582
7	5	1	0.051	111.791
8	5	1	0.051	111.791
9	5	1	0.054	111.176
10	5	1	0.054	111.176
11	5	1	0.055	110.979
12	5	1	0.057	110.597
13	5	1	0.057	110.597
14	5	1	0.058	110.412
15	5	1	0.061	109.876
16	5	1	0.058	110.412
17	5	1	0.057	110.597
18	5	1	0.056	110.786
19	5	1	0.061	109.876
20	5	1	0.061	109.876
22	5	1	0.065	109.205
23	5	1	0.064	109.368
24	5	1	0.060	110.051
25	5	1	0.051	111.791
26	5	1	0.045	113.149
27	5	1	0.046	112.910
28	5	1	0.045	113.149
29	5	1	0.048	112.447
30	5	1	0.050	112.005
31	5	1	0.061	109.876
1	6	1	0.066	109.044
2	6	1	0.063	109.534
3	6	1	0.063	109.534
4	6	1	0.058	110.412
5	6	1	0.065	109.205
6	6	1	0.069	108.577
7	6	1	0.071	108.278
9	6	1	0.067	108.886
10	6	1	0.059	110.230
11	6	1	0.062	109.704
12	6	1	0.061	109.876
13	6	1	0.060	110.051
14	6	1	0.054	111.176
15	6	1	0.060	110.051
16	6	1	0.063	109.534
19	6	1	0.063	109.534
20	6	1	0.058	110.412
21	6	1	0.059	110.230
22	6	1	0.041	114.170
26	6	1	0.039	114.723
27	6	1	0.050	112.005
28	6	1	0.055	110.979
29	6	1	0.058	110.412
30	6	1	0.060	110.051

APPENDIX 6.4 : (CONTINUED)

3	7	1	0.052	111.582
4	7	1	0.041	114.170
6	7	1	0.047	112.675
7	7	1	0.049	112.223
10	7	1	0.049	112.223
11	7	1	0.050	112.005
12	7	1	0.049	112.223
13	7	1	0.051	111.791
14	7	1	0.051	111.791
17	7	1	0.055	110.979
18	7	1	0.057	110.597
20	7	1	0.059	110.230
21	7	1	0.061	109.876
24	7	1	0.064	109.368
25	7	1	0.063	109.534
27	7	1	0.063	109.534
28	7	1	0.063	109.534
2	8	1	0.063	109.534
3	8	1	0.064	109.368
25	8	1	0.045	113.149
29	8	1	0.041	114.170
7	9	1	0.042	113.905
8	9	1	0.044	113.395
15	9	1	0.036	115.612
19	9	1	0.042	113.905
25	9	1	0.106	104.170
29	9	1	0.041	114.170
2	10	1	0.043	113.647
4	10	1	0.047	112.675
5	10	1	0.048	112.447
6	10	1	0.047	112.675
9	10	1	0.050	112.005
10	10	1	0.052	111.582
12	10	1	0.052	111.582
13	10	1	0.054	111.176
17	10	1	0.056	110.786
18	10	1	0.056	110.786
23	10	1	0.055	110.979
24	10	1	0.057	110.597
26	10	1	0.056	110.786
31	10	1	0.056	110.786
1	11	1	0.027	118.867
9	11	1	0.052	111.582
10	11	1	0.052	111.582
13	11	1	0.048	112.447
15	11	1	0.041	114.170
21	11	1	0.037	115.307
22	11	1	0.040	114.443
1	12	1	0.161	100.053
11	12	1	0.058	110.412
22	12	1	0.144	101.136

APPENDIX 6.5: SOIL MOISTURE TENSION(BAR) AND SOIL MOISTURE CONTENT (MM) FOR MACMERRY SUBSOIL (600 MM)

DAY	MONTH	YEAR	SOIL TENSION	SOIL MOISTURE
6	3	1	0.023	136.407
13	3	1	0.001	251.011
15	3	1	0.005	183.546
20	3	1	0.001	251.011
21	3	1	0.006	177.151
28	3	1	0.001	251.011
29	3	1	0.001	251.011
30	3	1	0.001	251.011
31	3	1	0.014	150.235
3	4	1	0.001	251.011
4	4	1	0.004	191.687
6	4	1	0.013	152.416
7	4	1	0.027	132.219
10	4	1	0.047	118.705
11	4	1	0.045	119.714
12	4	1	0.041	121.901
13	4	1	0.040	122.488
14	4	1	0.001	251.011
15	4	1	0.020	140.166
16	4	1	0.020	140.166
17	4	1	0.030	129.537
18	4	1	0.026	133.193
19	4	1	0.036	125.024
21	4	1	0.048	118.220
22	4	1	0.048	118.220
23	4	1	0.051	116.835
24	4	1	0.053	115.964
25	4	1	0.058	113.948
26	4	1	0.053	115.964
27	4	1	0.001	251.011
28	4	1	0.001	251.011

APPENDIX 6.5 : (CONTINUED)

3	5	1	0.017	144.668
4	5	1	0.022	137.592
5	5	1	0.001	251.011
6	5	1	0.001	251.011
7	5	1	0.010	160.396
8	5	1	0.014	150.235
9	5	1	0.025	134.213
10	5	1	0.028	131.287
11	5	1	0.034	126.422
12	5	1	0.034	126.422
13	5	1	0.038	123.716
14	5	1	0.038	123.716
15	5	1	0.039	123.092
16	5	1	0.044	120.238
17	5	1	0.050	117.285
18	5	1	0.054	115.543
19	5	1	0.063	112.130
20	5	1	0.068	110.477
22	5	1	0.077	107.838
23	5	1	0.062	112.480
24	5	1	0.008	167.511
25	5	1	0.016	146.384
26	5	1	0.030	129.537
27	5	1	0.035	125.711
28	5	1	0.041	121.901
29	5	1	0.045	119.714
30	5	1	0.053	115.964
31	5	1	0.069	110.163
1	6	1	0.074	108.675
2	6	1	0.088	105.073
3	6	1	0.094	103.734
4	6	1	0.099	102.693
5	6	1	0.107	101.153
6	6	1	0.119	99.083
7	6	1	0.127	97.837
9	6	1	0.149	94.844
10	6	1	0.072	109.255
11	6	1	0.161	93.426
12	6	1	0.170	92.442
13	6	1	0.091	104.390
14	6	1	0.182	91.224
15	6	1	0.195	90.008
16	6	1	0.202	89.393
19	6	1	0.216	88.235
20	6	1	0.214	88.395
21	6	1	0.230	87.164
22	6	1	0.001	251.011
26	6	1	0.005	183.546
27	6	1	0.016	146.384
28	6	1	0.022	137.592
29	6	1	0.025	134.213
30	6	1	0.028	131.287

APPENDIX 6.5 : (CONTINUED)

3	7	1	0.021	138.842
4	7	1	0.001	251.011
6	7	1	0.012	154.808
7	7	1	0.021	138.842
10	7	1	0.037	124.359
11	7	1	0.044	120.238
12	7	1	0.047	118.705
13	7	1	0.054	115.543
14	7	1	0.062	112.480
17	7	1	0.077	107.838
18	7	1	0.089	104.843
20	7	1	0.108	100.970
21	7	1	0.105	101.525
24	7	1	0.114	99.914
25	7	1	0.113	100.085
27	7	1	0.081	106.781
28	7	1	0.072	109.255
2	8	1	0.074	108.675
3	8	1	0.002	219.353
25	8	1	0.026	133.193
29	8	1	0.047	118.705
7	9	1	0.003	202.719
8	9	1	0.010	160.396
15	9	1	0.010	160.396
19	9	1	0.033	127.158
25	9	1	0.112	100.258
29	9	1	0.001	251.011
2	10	1	0.010	160.396
4	10	1	0.018	143.068
5	10	1	0.021	138.842
6	10	1	0.023	136.407
9	10	1	0.032	127.921
10	10	1	0.033	127.158
12	10	1	0.033	127.158
13	10	1	0.036	125.024
17	10	1	0.030	129.537
18	10	1	0.033	127.158
23	10	1	0.051	116.835
24	10	1	0.050	117.285
26	10	1	0.026	133.193
1	11	1	0.001	251.011
9	11	1	0.021	138.842
10	11	1	0.025	134.213
13	11	1	0.001	251.011
15	11	1	0.001	251.011
21	11	1	0.001	251.011
22	11	1	0.001	251.011
1	12	1	0.141	95.867
11	12	1	0.001	251.011
22	12	1	0.133	96.963

APPENDIX 6.6: SOIL MOISTURE TENSION(BAR) AND SOIL MOISTURE CONTENT (MM) FOR WINTON GRASS AT PLOUGH LAYER (300 MM)

DAY	MONTH	YEAR	SOIL TENSION	SOIL MOISTURE
6	3	1	0.053	104.406
13	3	1	0.045	105.921
15	3	1	0.033	108.853
20	3	1	0.026	111.162
21	3	1	0.034	108.567
28	3	1	0.028	110.439
29	3	1	0.030	109.770
30	3	1	0.023	112.368
31	3	1	0.042	106.567
3	4	1	0.036	108.023
4	4	1	0.041	106.793
6	4	1	0.048	105.321
7	4	1	0.048	105.321
10	4	1	0.106	98.226
11	4	1	0.076	101.146
12	4	1	0.054	104.235
13	4	1	0.059	103.425
14	4	1	0.057	103.740
15	4	1	0.052	104.582
16	4	1	0.051	104.761
17	4	1	0.053	104.406
18	4	1	0.049	105.130
19	4	1	0.051	104.761
21	4	1	0.057	103.740
22	4	1	0.046	105.716
23	4	1	0.047	105.517
24	4	1	0.048	105.321
25	4	1	0.050	104.943
26	4	1	0.073	101.505
27	4	1	0.063	102.830
28	4	1	0.032	109.148

APPENDIX 6.6 : (CONTINUED)

3	5	1	0.042	106.567
4	5	1	0.041	106.793
5	5	1	0.041	106.793
6	5	1	0.047	105.517
7	5	1	0.046	105.716
8	5	1	0.044	106.131
9	5	1	0.046	105.716
10	5	1	0.051	104.761
11	5	1	0.045	105.921
12	5	1	0.044	106.131
13	5	1	0.054	104.235
14	5	1	0.058	103.581
15	5	1	0.052	104.582
16	5	1	0.052	104.582
17	5	1	0.049	105.130
18	5	1	0.054	104.235
19	5	1	0.058	103.581
20	5	1	0.063	102.830
22	5	1	0.072	101.628
23	5	1	0.073	101.505
24	5	1	0.065	102.547
25	5	1	0.058	103.581
26	5	1	0.063	102.830
27	5	1	0.069	102.010
28	5	1	0.071	101.753
29	5	1	0.077	101.029
30	5	1	0.088	99.849
31	5	1	0.100	98.731
1	6	1	0.109	97.985
2	6	1	0.132	96.348
3	6	1	0.164	94.524
4	6	1	0.186	93.482
5	6	1	0.207	92.606
6	6	1	0.236	91.544
7	6	1	0.263	90.675
9	6	1	0.351	88.400
10	6	1	0.406	87.274
11	6	1	0.609	84.214
12	6	1	0.662	83.598
13	6	1	0.734	82.842
14	6	1	0.773	82.465
15	6	1	0.795	82.261
16	6	1	0.817	82.064
19	6	1	0.578	84.602
20	6	1	0.812	82.108
21	6	1	0.828	81.967
22	6	1	0.820	82.038
26	6	1	0.551	84.960
27	6	1	0.433	86.781
28	6	1	0.443	86.607
29	6	1	0.468	86.189
30	6	1	0.484	85.935

APPENDIX G.6 : (CONTINUED)

3	7	1	0.487	85.888
4	7	1	0.480	85.997
6	7	1	0.348	88.467
7	7	1	0.360	88.203
10	7	1	0.369	88.012
11	7	1	0.371	87.970
12	7	1	0.381	87.764
13	7	1	0.376	87.866
14	7	1	0.366	88.075
17	7	1	0.303	89.552
18	7	1	0.277	90.262
20	7	1	0.614	84.154
21	7	1	0.624	84.034
24	7	1	0.687	83.326
25	7	1	0.649	83.744
27	7	1	0.781	82.390
28	7	1	0.838	81.881
2	8	1	0.653	83.699
3	8	1	0.700	83.188
25	8	1	0.515	85.466
29	8	1	0.764	82.550
7	9	1	0.735	82.832
8	9	1	0.733	82.852
15	9	1	0.710	83.084
19	9	1	0.550	84.973
25	9	1	0.561	84.825
29	9	1	0.554	84.919
2	10	1	0.559	84.852
4	10	1	0.545	85.041
5	10	1	0.524	85.336
9	10	1	0.481	85.982
10	10	1	0.482	85.966
17	10	1	0.446	86.555
23	10	1	0.442	86.624
24	10	1	0.440	86.659
26	10	1	0.379	87.805
31	10	1	0.405	87.293
1	11	1	0.408	87.237
16	11	1	0.024	111.948
21	11	1	0.018	114.819
5	12	1	0.049	105.130
11	12	1	0.015	116.677
22	12	1	0.023	112.368

APPENDIX 6.7: SOIL MOISTURE TENSION(BAR) AND SOIL MOISTURE CONTENT (MM) FOR WINTON GRASS SUBSOIL (600 MM)

DAY	MONTH	YEAR	SOIL TENSION	SOIL MOISTURE
6	3	1	0.006	230.579
13	3	1	0.001	247.179
15	3	1	0.001	247.179
20	3	1	0.001	247.179
21	3	1	0.002	240.620
28	3	1	0.001	247.179
29	3	1	0.005	232.216
30	3	1	0.001	247.179
31	3	1	0.020	220.055
3	4	1	0.001	247.179
4	4	1	0.005	232.216
6	4	1	0.017	221.447
7	4	1	0.025	218.158
10	4	1	0.026	217.826
11	4	1	0.025	218.158
12	4	1	0.032	216.079
13	4	1	0.038	214.643
14	4	1	0.021	219.639
15	4	1	0.018	220.957
16	4	1	0.022	219.243
17	4	1	0.011	225.219
18	4	1	0.025	218.158
19	4	1	0.035	215.328
21	4	1	0.047	212.880
22	4	1	0.050	212.369
23	4	1	0.081	208.431
24	4	1	0.042	213.811
25	4	1	0.073	209.274
26	4	1	0.039	214.426
27	4	1	0.050	212.369
28	4	1	0.001	247.179

APPENDIX 6.7 : (CONTINUED)

3	5	1	0.004	234.235
4	5	1	0.007	229.204
5	5	1	0.001	247.179
6	5	1	0.001	247.179
7	5	1	0.007	229.204
8	5	1	0.007	229.204
9	5	1	0.013	223.764
10	5	1	0.016	221.969
11	5	1	0.025	218.158
12	5	1	0.032	216.079
13	5	1	0.023	218.865
14	5	1	0.024	218.504
15	5	1	0.058	211.150
16	5	1	0.063	210.473
17	5	1	0.081	208.431
18	5	1	0.093	207.317
19	5	1	0.128	204.763
20	5	1	0.148	203.613
22	5	1	0.169	202.567
23	5	1	0.202	201.170
24	5	1	0.176	202.249
25	5	1	0.192	201.567
26	5	1	0.228	200.227
27	5	1	0.261	199.180
28	5	1	0.292	198.315
29	5	1	0.304	198.005
30	5	1	0.357	196.774
31	5	1	0.418	195.573
1	6	1	0.446	195.082
2	6	1	0.480	194.527
3	6	1	0.513	194.026
4	6	1	0.531	193.766
5	6	1	0.557	193.407
6	6	1	0.737	191.317
7	6	1	0.426	195.430
9	6	1	0.728	191.408
10	6	1	0.732	191.368
11	6	1	0.744	191.247
12	6	1	0.525	193.852
13	6	1	0.390	196.100
14	6	1	0.536	193.696
15	6	1	0.378	196.338
16	6	1	0.737	191.317
19	6	1	0.774	190.954
20	6	1	0.430	195.359
21	6	1	0.658	192.161
22	6	1	0.425	195.447
26	6	1	0.393	196.042
27	6	1	0.420	195.537
28	6	1	0.438	195.219
29	6	1	0.459	194.865
30	6	1	0.481	194.511

APPENDIX 6.7 : (CONTINUED)

3	7	1	0.477	194.574
4	7	1	0.186	201.815
6	7	1	0.017	221.447
7	7	1	0.020	220.055
10	7	1	0.088	207.762
11	7	1	0.110	205.971
12	7	1	0.130	204.640
13	7	1	0.167	202.661
14	7	1	0.219	200.541
17	7	1	0.422	195.501
18	7	1	0.490	194.371
20	7	1	0.583	193.065
21	7	1	0.607	192.763
24	7	1	0.658	192.161
25	7	1	0.670	192.026
27	7	1	0.598	192.875
28	7	1	0.581	193.091
2	8	1	0.660	192.138
3	8	1	0.038	214.643
25	8	1	0.360	196.710
29	8	1	0.492	194.341
7	9	1	0.485	194.449
8	9	1	0.473	194.638
15	9	1	0.180	202.072
19	9	1	0.065	210.218
25	9	1	0.162	202.900
29	9	1	0.001	247.179
2	10	1	0.008	228.019
4	10	1	0.015	222.525
5	10	1	0.017	221.447
9	10	1	0.052	212.046
10	10	1	0.061	210.737
17	10	1	0.108	206.117
23	10	1	0.159	203.047
24	10	1	0.181	202.029
26	10	1	0.202	201.170
31	10	1	0.232	200.093
1	11	1	0.105	206.343
16	11	1	0.001	247.179
21	11	1	0.001	247.179
5	12	1	0.001	247.179
11	12	1	0.001	247.179
22	12	1	0.001	247.179

APPENDIX 6.8: SOIL MOISTURE TENSION(BAR) AND SOIL MOISTURE CONTENT (MM) FOR WINTON SOIL AT PLOUGH LAYER (300 MM)

DAY	MONTH	YEAR	SOIL TENSION	SOIL MOISTURE
6	3	1	0.032	109.148
13	3	1	0.034	108.567
15	3	1	0.036	108.023
20	3	1	0.024	111.948
21	3	1	0.037	107.762
28	3	1	0.028	110.439
29	3	1	0.017	115.398
30	3	1	0.024	111.948
31	3	1	0.030	109.770
3	4	1	0.036	108.023
4	4	1	0.036	108.023
6	4	1	0.047	105.517
7	4	1	0.053	104.406
10	4	1	0.053	104.406
11	4	1	0.046	105.716
12	4	1	0.062	102.975
13	4	1	0.058	103.581
14	4	1	0.063	102.830
15	4	1	0.062	102.975
16	4	1	0.050	104.943
17	4	1	0.048	105.321
18	4	1	0.047	105.517
19	4	1	0.049	105.130
21	4	1	0.050	104.943
22	4	1	0.040	107.025
23	4	1	0.039	107.264
24	4	1	0.048	105.321
25	4	1	0.060	103.272
26	4	1	0.049	105.130
27	4	1	0.050	104.943
28	4	1	0.033	108.853

APPENDIX 6.8 : (CONTINUED)

3	5	1	0.027	110.793
4	5	1	0.039	107.264
5	5	1	0.099	98.819
6	5	1	0.036	108.023
7	5	1	0.100	98.731
8	5	1	0.041	106.793
9	5	1	0.046	105.716
10	5	1	0.046	105.716
11	5	1	0.051	104.761
12	5	1	0.051	104.761
13	5	1	0.048	105.321
14	5	1	0.048	105.321
15	5	1	0.053	104.406
16	5	1	0.049	105.130
17	5	1	0.053	104.406
18	5	1	0.047	105.517
19	5	1	0.115	97.524
20	5	1	0.051	104.761
22	5	1	0.063	102.830
23	5	1	0.058	103.581
24	5	1	0.043	106.346
25	5	1	0.040	107.025
26	5	1	0.045	105.921
27	5	1	0.049	105.130
28	5	1	0.052	104.582
29	5	1	0.045	105.921
30	5	1	0.048	105.321
31	5	1	0.053	104.406
1	6	1	0.051	104.761
2	6	1	0.052	104.582
3	6	1	0.052	104.582
4	6	1	0.057	103.740
5	6	1	0.059	103.425
6	6	1	0.064	102.687
7	6	1	0.087	99.949
9	6	1	0.055	104.067
10	6	1	0.055	104.067
11	6	1	0.061	103.122
12	6	1	0.066	102.410
13	6	1	0.043	106.346
14	6	1	0.047	105.517
15	6	1	0.053	104.406
16	6	1	0.054	104.235
19	6	1	0.054	104.235
20	6	1	0.030	109.770
21	6	1	0.043	106.346
22	6	1	0.032	109.148
26	6	1	0.035	108.291
27	6	1	0.038	107.510
28	6	1	0.033	108.853
29	6	1	0.038	107.510
30	6	1	0.041	106.793

APPENDIX G.8: (CONTINUED)

3	7	1	0.039	107.264
4	7	1	0.027	110.793
6	7	1	0.030	109.770
7	7	1	0.033	108.853
10	7	1	0.039	107.264
11	7	1	0.044	106.131
12	7	1	0.038	107.510
13	7	1	0.038	107.510
14	7	1	0.051	104.761
17	7	1	0.043	106.346
18	7	1	0.048	105.321
20	7	1	0.050	104.943
21	7	1	0.036	108.023
24	7	1	0.048	105.321
25	7	1	0.049	105.130
27	7	1	0.058	103.581
28	7	1	0.054	104.235
2	8	1	0.045	105.921
3	8	1	0.073	101.505
25	8	1	0.043	106.346
29	8	1	0.038	107.510
7	9	1	0.036	108.023
8	9	1	0.040	107.025
15	9	1	0.035	108.291
19	9	1	0.040	107.025
25	9	1	0.043	106.346
29	9	1	0.026	111.162
2	10	1	0.032	109.148
4	10	1	0.040	107.025
5	10	1	0.036	108.023
9	10	1	0.039	107.264
10	10	1	0.049	105.130
17	10	1	0.044	106.131
23	10	1	0.042	106.567
24	10	1	0.038	107.510
26	10	1	0.043	106.346
31	10	1	0.040	107.025
1	11	1	0.035	108.291
16	11	1	0.028	110.439
21	11	1	0.030	109.770
5	12	1	0.027	110.793
11	12	1	0.006	126.478
22	12	1	0.080	100.690

APPENDIX G.9: SOIL MOISTURE TENSION(BAR) AND SOIL MOISTURE CONTENT (MM) FOR WINTON SUBSOIL (600 MM)

DAY	MONTH	YEAR	SOIL TENSION	SOIL MOISTURE
6	3	1	0.121	205.210
13	3	1	0.093	207.317
15	3	1	0.002	240.620
20	3	1	0.001	247.179
21	3	1	0.007	229.204
29	3	1	0.001	247.179
30	3	1	0.001	247.179
31	3	1	0.001	247.179
3	4	1	0.001	247.179
4	4	1	0.003	236.864
6	4	1	0.014	223.122
7	4	1	0.014	223.122
10	4	1	0.040	214.216
11	4	1	0.028	217.201
12	4	1	0.017	221.447
13	4	1	0.016	221.969
14	4	1	0.001	247.179
15	4	1	0.001	247.179
16	4	1	0.004	234.235
17	4	1	0.023	218.865
18	4	1	0.001	247.179
19	4	1	0.009	226.980
21	4	1	0.020	220.055
22	4	1	0.025	218.158
23	4	1	0.030	216.620
24	4	1	0.001	247.179
25	4	1	0.033	215.821
26	4	1	0.074	209.163
27	4	1	0.072	209.386
28	4	1	0.001	247.179

APPENDIX G.9 : (CONTINUED)

3	5	1	0.001	247.179
4	5	1	0.001	247.179
5	5	1	0.051	212.206
6	5	1	0.001	247.179
7	5	1	0.065	210.218
8	5	1	0.003	236.864
9	5	1	0.012	224.460
10	5	1	0.020	220.055
11	5	1	0.018	220.957
12	5	1	0.020	220.055
13	5	1	0.039	214.426
14	5	1	0.048	212.706
15	5	1	0.022	219.243
16	5	1	0.022	219.243
17	5	1	0.023	218.865
18	5	1	0.023	218.865
19	5	1	0.089	207.671
20	5	1	0.028	217.201
22	5	1	0.037	214.865
23	5	1	0.035	215.328
24	5	1	0.001	247.179
25	5	1	0.003	236.864
26	5	1	0.004	234.235
27	5	1	0.011	225.219
28	5	1	0.011	225.219
29	5	1	0.015	222.525
30	5	1	0.016	221.969
31	5	1	0.021	219.639
1	6	1	0.027	217.508
2	6	1	0.032	216.079
3	6	1	0.035	215.328
4	6	1	0.039	214.426
5	6	1	0.045	213.239
6	6	1	0.051	212.206
7	6	1	0.059	211.010
9	6	1	0.076	208.947
10	6	1	0.081	208.431
11	6	1	0.089	207.671
12	6	1	0.094	207.231
13	6	1	0.099	206.814
14	6	1	0.111	205.899
15	6	1	0.121	205.210
16	6	1	0.131	204.579
19	6	1	0.161	202.949
20	6	1	0.001	247.179
21	6	1	0.001	247.179
22	6	1	0.001	247.179
26	6	1	0.001	247.179
27	6	1	0.001	247.179
28	6	1	0.001	247.179
29	6	1	0.001	247.179
30	6	1	0.001	247.179

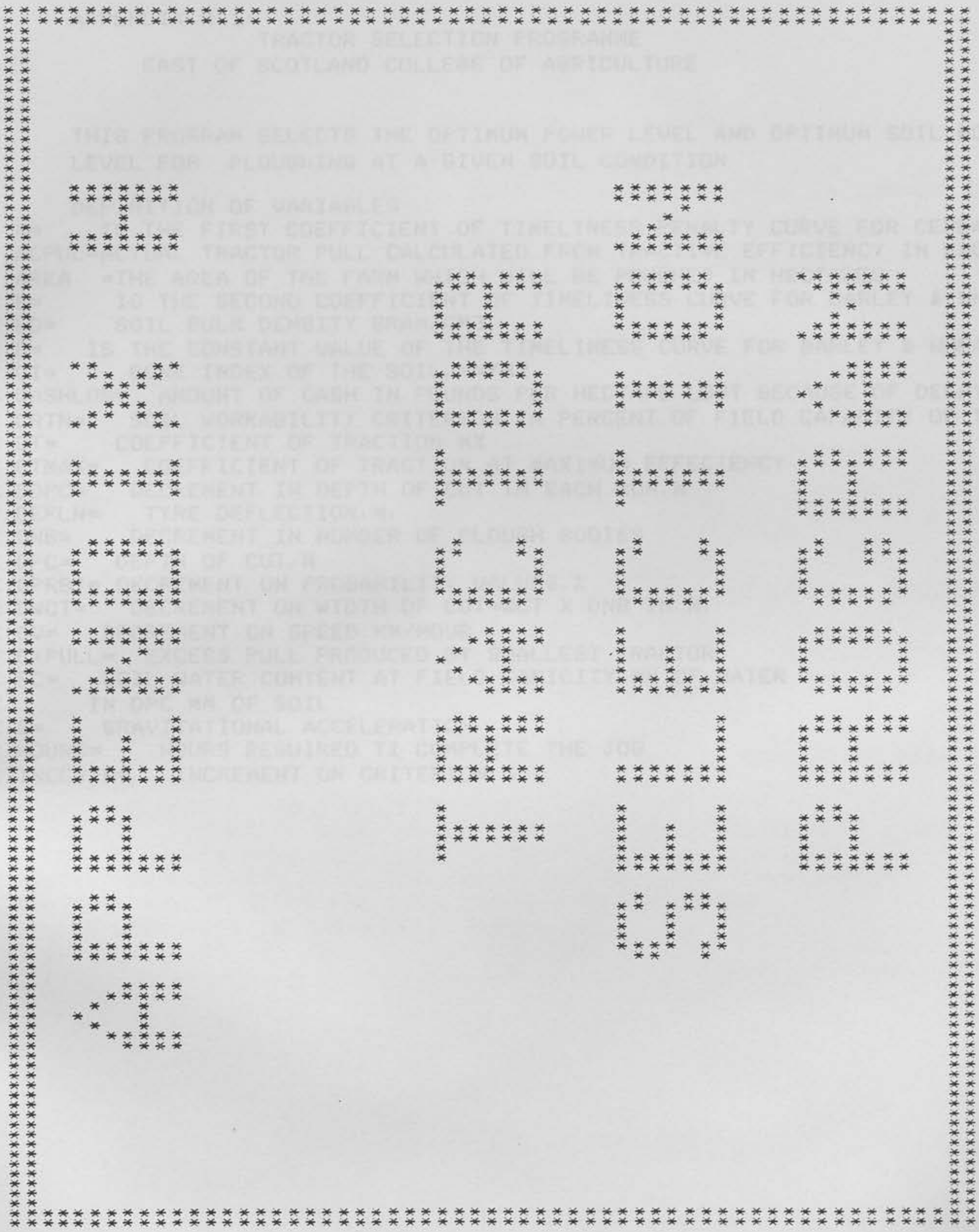
APPENDIX 6.9 : (CONTINUED)

3	7	1	0.001	247.179
4	7	1	0.001	247.179
6	7	1	0.001	247.179
7	7	1	0.001	247.179
10	7	1	0.001	247.179
11	7	1	0.003	236.864
12	7	1	0.001	247.179
13	7	1	0.003	236.864
14	7	1	0.014	223.122
17	7	1	0.055	211.585
18	7	1	0.066	210.094
20	7	1	0.082	208.332
21	7	1	0.090	207.581
24	7	1	0.108	206.117
25	7	1	0.125	204.952
27	7	1	0.080	208.531
28	7	1	0.080	208.531
2	8	1	0.104	206.420
3	8	1	0.036	215.093
25	8	1	0.021	219.639
29	8	1	0.038	214.643
7	9	1	0.007	229.204
8	9	1	0.011	225.219
15	9	1	0.012	224.460
19	9	1	0.026	217.826
25	9	1	0.050	212.369
29	9	1	0.005	232.216
2	10	1	0.008	228.019
4	10	1	0.013	223.764
5	10	1	0.017	221.447
9	10	1	0.026	217.826
10	10	1	0.031	216.345
17	10	1	0.030	216.620
23	10	1	0.043	213.616
24	10	1	0.034	215.571
26	10	1	0.036	215.093
31	10	1	0.034	215.571
1	11	1	0.002	240.620
16	11	1	0.001	247.179
21	11	1	0.001	247.179
5	12	1	0.001	247.179
11	12	1	0.001	247.179
22	12	1	0.072	209.386

APPENDIX G.10: RUNNING INSTRUCTIONS AND INPUT DATA FOR TENSION PROGRAM 2

```
DEFINE INPUT AND OUTPUT FILES AS FOLLOWS:
    DEFINE(FT04,OUT1,,C);
    DEFINE(FT09,INPUT);
    DEFINE(FT12,OUT2).
WHERE:  FILE 'OUT1' IS AN OUTPUT FILE IN THE FORM OF APPENDICES
           G.2 TO G.9;
        FILE 'OUT2' IS AN OUTPUT FILE READABLE BY THE GRAPH PROGRAM
        FILE 'INPUT' IS AN INPUT FILE WHICH CONTAINS DAILY SOIL
           MOISTURE TENSION DATA PRODUCED BY THE PRAGRAM 'TENSION 1'.

OTHER INPUT DATA ARE READ THROUGH THE CONSOL AS IN THE FOLLOWING EXAMPLE:
    SOIL MOISTURE TENSION(BAR) AND SOIL MOISTURE
        CONTENT (MM) FOR WINTON  SUBSOIL (600 MM)
     1.59   2.98660  -0.0388060.0
     1
WHERE:  THE FIRST TWO LINES ARE HEADINGS FOR THE FILE  'OUT1';
        LINE 3 CONTAINS  SOIL BULK DENSITY AND TWO COEFFICIENTS OF THE SOIL
           MOISTURE CHARACTERISTICS CURVE AND DEPTH;
        LINE 4 IS THE NUMBER OF YEARS FOR WHICH DATA IS AVAILABLE.
```



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      APPENDIX H.1:
C                   TRACTOR SELECTION PROGRAMME
C            EAST OF SCOTLAND COLLEGE OF AGRICULTURE
C
C
C     THIS PROGRAM SELECTS THE OPTIMUM POWER LEVEL AND OPTIMUM SOIL MOISTURE
C     LEVEL FOR  PLOUGHING AT A GIVEN SOIL CONDITION
C
C     DEFINITION OF VARIABLES
C A=    IS THE FIRST COEFFICIENT OF TIMELINESS PENALTY CURVE FOR CEREALS
C ACPUL=ACTUAL TRACTOR PULL CALCULATED FROM TRACTIVE EFFICIENCY IN EACH TIME
C AREA  =THE AREA OF THE FARM WHICH WILL BE POUGHED IN HECTARES
C B=     IS THE SECOND COEFFICIENT OF TIMELINESS CURVE FOR BARLEY & WHEAT
C BD=    SOIL BULK DENSITY GRAM/CM3
C C=   IS THE CONSTANT VALUE OF THE TIMELINESS CURVE FOR BARLEY & WHEAT
C CI=     CONE INDEX OF THE SOIL,KN/M2
C CASHLOS=  AMOUNT OF CASH IN POUNDS PER HECTARE LOST BECAUSE OF DELAY
C CRTN=   SOIL WORKABILITY CRITERION IN PERCENT OF FIELD CAPACITY OF THE SOIL
C CT=    COEFFICIENT OF TRACTION M%
C CTMAX=   COEFFICIENT OF TRACTION AT MAXIMUM EFFECIENCY
C DDPC=   DECREMENT IN DEPTH OF CUT IN EACH RUN,M
C DEFLN=   TYRE DEFLECTION,M,
C DNB=    DECREMENT IN NUMBER OF PLOUGH BODIES
C DPC=   DEPTH OF CUT,M
C DPRBT= DECREMENT ON PROBABILITY VALUES,%
C DWCT=   DECREMENT ON WIDTH OF CUT=WCT X DNB IN M,
C DV=   DECREMENT ON SPEED KM/HOUR
C EXPULL= EXCESS PULL PRODUCED BY SMALLEST TRACTOR
C FC=   SOIL WATER CONTENT AT FIELD CAPICITY MM OF WATER
C     IN DPC MM OF SOIL
C G=   GRAVITATIONAL ACCELERATION
C HOURS=   HOURS REQUIRED TI COMPLETE THE JOB
C INCCRTN=   INCREMENT ON CRITERION %
```

APPENDIX H.1 (CONTINUED)

```
C INCTW=   INCREMENT ON TYRE WIDTH M,
C INCWT=   INCREMENT ON TRACTOR WEIGHT KN
C INTPUL=   INCREMENT ON TRACTOR'S THEORETICAL PULL
C LDA1=    FIRST LATERAL DIRECTIONAL ANGLE IN RADIAN
C LSA2=    SECOND LATERAL DIRECTIONAL ANGLE
C LOSDN=  LOSS OF GRAIN YIELD IF OPERATION CARRIED OUT ON WKN
C M=  SOIL MOISTURE CONTENT IN TERMS OF GRAMS OF WATER IN 100 GMS OF SOIL
C MACRTN=  MAXIMUM POSSIBLE SOIL WORKABILITY CRITERION ,
C MAPRBT=  MAXIMUM POSSIBLE PROBABILITY LEVEL IS USUALLY 100%
C MACH=  PRESENT ANNUAL COST OF MACHINE CALCULATED FROM MACHINERY COSTING
C MATPUL=  MAXIMUM THEORETICAL PULL AVAILABLE
C MAXDPC=  MAXIMUM EXPECTED DEPTH OF CUT
C MAXNB=  MAXIMUM NUMBER OF PLOUGH BODIES POSSIBLE
C MAXTWD=  MAXIMUM ACCEPTABLE TYRE WIDTH M,
C MAXV=  MAXIMUM SPEED KM/N
C MAXWT=   MAXIMUM TRACTOR WEIGHT FOR EACH TRACTOR
C MICRTN= MINIMUM CRITERION FOR WORKDAYS % OF FC
C MINDPC=  MINIMUM ACCEPTABLE DEPTH OF CUT M,
C MINND=  MINIMUM ACCEPTABLE NUMBER OF PLOUGH BODIES
C MINTWD=  MINIMUM ACCEPTABLE TYRE WIDTH M/ 1 VALUE
C MINV=  MINIMUM ACCEPTABLE SPEED KM/N
C MINWT=  MINIMUM ACCEPTABLE TRACTOR WEIGHT
C MIPRBT=  MINIMUM ACCEPTABLE PROBABILITY LEVEL
C MITPUL=  MINIMUM POSSIBLE THEORETICAL PULL PRODUCED BY EACH TRACTOR
C   KW
C MN=  MOBILITY NUMBER 100
C NB=  NUMBER OF PLOUGH BODIES
C NDAY=  NUMBER OF DAYS REQUIRED TO FINISH PLOUGHING
C NWRD=  A NON WORKING DAY
C PAFC=  PLOUGH ACTUAL FIELD CAPACITY HA PER HOUR
C PFAC=  PERCENTAGE FACTOR IF FIELD CAPACITY WAS IN PERCENTAGE,READ 'PE'
C OTHERWISE READ 'MM'
C PFE=  PLOUGH'S FIELD EFFICIENCY %
C PHOURS=  POTENTIAL HOURS OF WORKING IN A DAY IT IS USUALLY 8 HRS
C PPFC= PLOUGH'S POTENTIAL FIELD CAPACITY HECTARES PER HOUR
C PRBTY= PROBABILITY LEVEL FOR WHICH FARM MACHINERY IS PLANNED
C SCRTN=  NO. OF STEPS FOR SOIL WORKABILITY CRITERION
C     IS EXPRESSED IN TERMS OF % OF FC
```

APPENDIX H.1 (CONTINUED)

```
C SDPC=   NO. OF STEPS FOR DEPTH OF CUT
C SLIP=   TRAVEL REDUCTION INDUCED BY WHEEL SLIP %
C SNB=   NO. OF STEPS FOR NO. OF BODIES
C SPRBT=   NO. OF STEPS FOR PROBABILITY
C SPW=  SPECIFIC WEIGHT OF SOIL IF IT IS NOT AVAILABLE PUNCH A 1 DIGIT
C       NEGATIVE VALUE
C STPULL= NO. OF STEPS FOR THEORETICAL PULL OF TRACTOR
C STWD=   NO. OF STEPS FOR WIDTH OF CUT
C SWT=  NO. OF STEPS FOR WIDTH OF TRACTOR
C SV    NO. OF STEPS FOR TRACTOR PLOUGHING SPEED
C TCASH=  TOTAL CASH LOSS DUE TO DELAY IN OPERATION
C TD=   TYRE DIAMETER M
C TDRFT=   TOTAL DRAUGHT REQUIRED
C TEF=  TRACTOR'S TRACTIVE EFFICIENCY
C TEST=   MOISTURE LEVEL ABOVE WHICH SOIL IS NONWORKABLE MM OF WATER IN
C       PLOUGH LAYER
C TH=   TYRE SECTION HEIGHT METERS
C TPULL=   THEORETICAL PULL OF TRACTOR KW
C TWD=  TYRE WIDTH M
C UDRFT=   UNIT DRAUGHT REQUIRED
C WCT=  WIDTH OF CUT M,
C WD=   A WORKING DAY
C WT=   TRACTOR WEIGHT KG
C WK1=   STARTING WEEK NUMBER (IN THE SEASON)
C WK2=   FINISHING WEEK NO  (LAST WEEK OF THE SEASON)
C WKN=  THE WEEK NO. IN WHICH THE OPERATION TAKES PLACE
      INTEGER*4 SNB, SDPC, SV, STWD, SWT, WTAB(10, 54, 10), ACOST, PLPAC
      INTEGER*4 WT, POWER, DPLOW, ORVAL, PAC, TFCOST, TLCOST, TCASH, CI
      INTEGER*4 MAXNB, MINNB, DNB, AREA, WK1, WK2, MAXWT, MINWT, INCWT
      INTEGER*4 NB, PRBTY, PFAC, MAPRBT, MIPRBT, DPRBT, JS, IS, WKM
      REAL*4 MATPUL, MITPUL, INTPUL, SPW1, LDA, G, V, TR, TY
      REAL*4 WCT, MAXDPC, MINDPC, DDPC, LDA1, LDA2, PFE, BD, MAXV, MINV, DV
      REAL*4 MICRTN, MACRTN, INCRTN, FC, A, B, C, SPW
      REAL*4 MAXTWD, MINTWD, INCTWD, DFLN, TEF, ACPUL
      REAL*4 TH, TD, TN, PPFC, PAFC, HOURS, M, PRICE, CTAB(11)
      REAL*4 CRTN, DPC, TWD, TPNL, UDRFT, MN, PHOUR
      COMMON/COMAC/ MACRTN, IS, JS, NDAY, CRTN, INCRTN, WK1, WK2, MICRTN, J
      COMMON/COMAN/ MINTWD, WKM, PRICE, A, B, C, TPULL, TEF, DPC, UDRFT, CI
      COMMON/CAMON/ MAPRBT, MIPRBT, DPRBT, PRBTY, MINNB, MINV, M
```

APPENDIX H.1 (CONTINUED)

```
      COMMON/COMNES/NB,HOURS,POWER,PAFC,WT,MINWT,AREA,TFCOST,
     1TLCOST,TCASH,ORVAL,PAC,TD,TH,MACH,IGROUP,ITYPE,IW,LIFE
     1,DNBCAP,DNICAP,DNFLAT,ALCH,UFCOST,DPLOW,LI,ACPUL,PLPAC,V
      COMMUN/COM/ KGROUP,KTYPE,KIW,KORVAL,KPAC
      COMMON/COMN/ WTAB,CTAB,TY,IX,FC,LDA,WCT,SLIP,SPW1,PFE
      DIMENSION XTH(5),XTD(5),XWT(5),XTWD(5),XDFLN(5),MACH(6)
      DATA XTH/0.280,0.280,0.356,0.381,0.457/
      DATA XTD/1.26,1.465,1.585,1.550,1.605/
      DATA XWT/10,11,18,24,32/
      DATA XTWD/0.351,0.361,0.472,0.516,0.638/
      DATA XDFLN/0.035,0.037,0.053,0.061,0.079/
C READ COSTING DATA FOR COSTING ROUTINE
      READ(5,50)MACH
      READ(5,51)IGROUP,ITYPE,IW
      READ(5,53)LIFE
      READ(5,54)DNBCAP,DNICAP,DNFLAT
      READ(5,55)ALCH,UFCOST
      KGROUP=IGROUP
      KTYPE=ITYPE
      KIW=IW
C READ PLOUGH SPECIFICATIONS
  690 READ(10,101)MAXNB,MINNB,DNB,MAXDPC,MINDPC,DDPC,LDA1,LDA2,PFE,
     1BD,MAXV,MINV,DV
CX       WRITE(12,101)MAXNB,MINNB,DNB,MAXDPC,MINDPC,DDPC,LDA1,LDA2,PFE,
CX     1BD,MAXV,MINV,DV
      READ(10,102)MICRTN,MACRTN,INCRTN,FC,PFAC,MAPRBT,MIPRBT,DPRBT,SPW,
     1 AREA,PHOUR
CX       WRITE(12,102)MICRTN,MACRTN,INCRTN,FC,PFAC,MAPRBT,MIPRBT,DPRBT,SPW,
CX     1AREA,PHOUR
C READ STARTING AND FINISHING WEEK NUMBERS
      READ(10,103)WK1,WK2,WKM,PRICE
CX       WRITE(12,103)WK1,WK2,WKM,PRICE
C READ TIMELINESS PENALTY CURVES COEFFICIENTS
C THE GENERAL SHAPE OF THE CURVE IS
C Y=A*WKN**2+B*WKN+C
      READ(10,106)A,B,C
CX       WRITE(12,106)A,B,C
      MINWT=10
      MINTWD=0.351
      SLIP=0.12
      PRBTY=0
      WRITE(12,897)AREA
      WRITE(12,898)WK1,WK2
      WRITE(12,899)
      WRITE(12,990)
      WRITE(12,991)
      SLIP=0.12
      NC=0
      LI=0
      POWER=110
```

APPENDIX H.1 (CONTINUED)

```
      CRTN=MICRTN
      JS=(MACRTN-MICRTN)/INCRTN
      IS=(MAPRBT-MIPRBT)/DPRBT
CX      WRITE(12,107)IS,JS
      READ(6,108)(CTAB(J),J=1,JS)
      DO 15 K=1,52
      DO 10 I=1,IS
      READ(6,109,END=190)(WTAB(I,K,J),J=1,JS)
CX      WRITE(9,109)(WTAB(I,K,J),J=1,JS)
   10 CONTINUE
   15 CONTINUE
C READ PERCENTAGE FACTOR READ 'PE' IF SOIL FC IS READ IN PERCENTAGE OT
C OTHERWISE READ 'MM' .
  190 WKN=WK1
      G=9.81
C CALCULATE NO. OF STEPS SHOULD BE TAKEN
      SNB=AINT((MAXNB-MINNB)*1.0/DNB+0.5)
      SDPC=AINT((MAXDPC-MINDPC)*1.0/DDPC+0.5)
      SV=AINT((MAXV-MINV)*1.0/DV+0.5)
CX      STWD=AINT((MAXTWD-MINTWD)*1.0/INCTWD+0.5)
CX      STPUL=AINT((MATPUL-MITPUL)*1.0/INTPUL+0.5)
CX      SWT=AINT((MAXWT-MINWT)*1.0/INCWT+0.5)
C CALCULATE SPECIFIFIC WT OF SOIL FROM BULK DENSITY IF NOT READ IN (-1)
      IF(SPW.EQ.0)GOTO 6
      SPW1=SPW
      GOTO 7
    6 SPW1=(BD*100)/9.807
    7 V=(MAXV-(MAXV*SLIP))
      DO 84 IV=1,SV
      NB=MAXNB
      DO 83 IN=1,SNB
      DPC=MAXDPC
      DO 82 ID=1,SDPC
C CALCULATE CONE INDEX
      DO 81 IX=1,5
      DO 80 J=1,JS
      CRTN=CTAB(J)
      TEST=CRTN*FC
   30 M=TEST/(BD*0.30*10)
      IF(PFAC.EQ.00) M=TEST
      CI=-84.54*M**0.75+149*SPW1
      TH=XTH(IX)
      TD=XTD(IX)
      WT=XWT(IX)
      TWD=XTWD(IX)
      DFLN=XDFLN(IX)
```

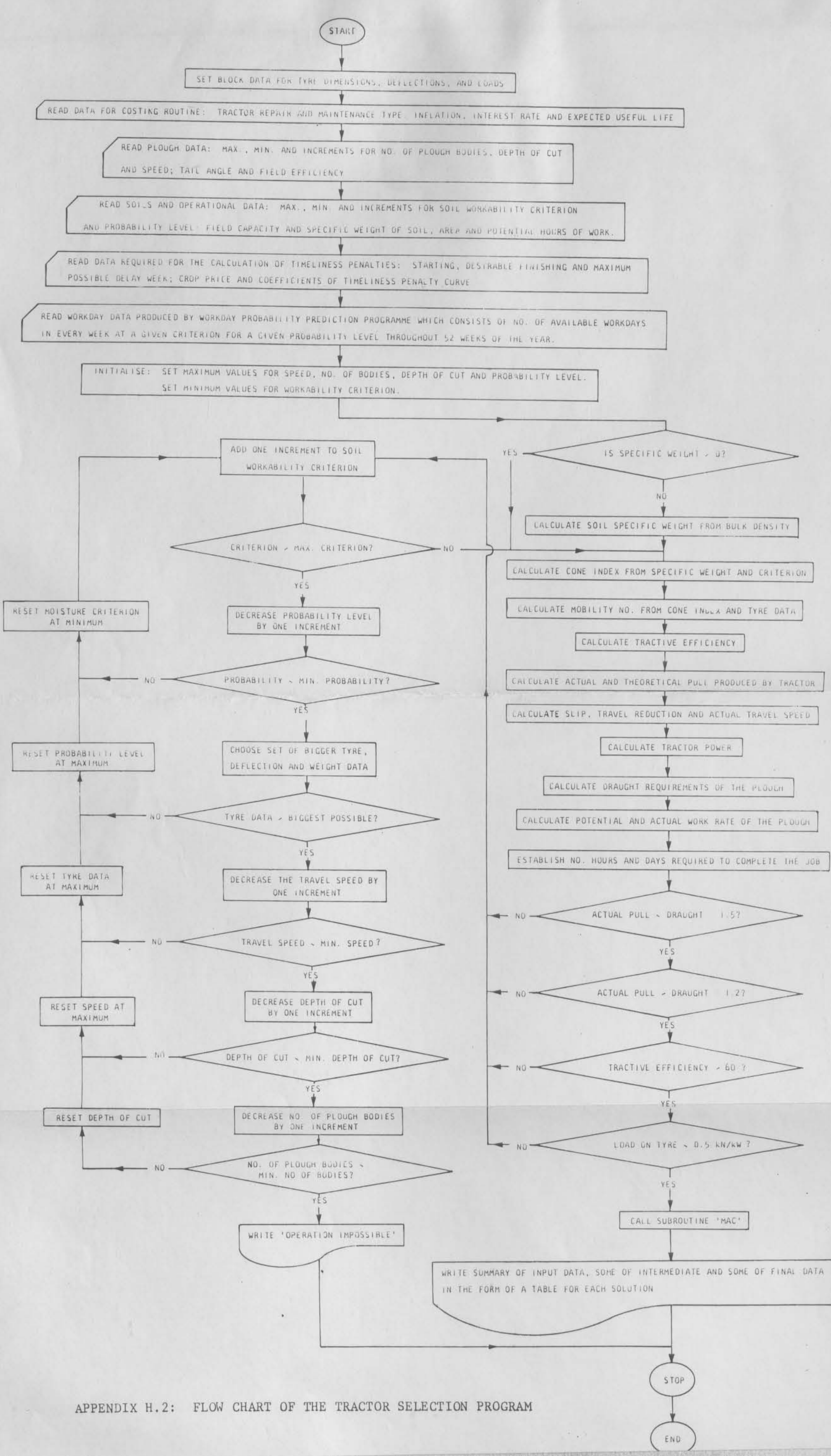
```
      LDA=0.92
      IF(V.GT.1.7)LDA=0.62
      WCT=1.1*DPC
C MOBILITY NO.
      MN=(((CI*TWD*TD)/WT)*(1/(1+TWD/(2*TD)))*((DFLN/TH)**0.5))
C TRACTIVE EFFICIENCY
      TEF=(78-(55/MN))/100
C ACTUAL PULL
      ACPUL=((0.41-(0.21/MN))*WT)*2
      TPULL=ACPUL/TEF
      POWER=(TPULL*V)*1.0+0.5
C DRAFT REQUIREMENTS
      UDRFT=((0.05*CI+(9.66*SPW1*V**2*(1-COS(LDA))/G))*DPC*WCT)*NB
C CALCULATE WHEEL SLIP
      SLIP=(9+(19/MN))/100
      TR=SLIP*V
C PLOUGHING POTENTIAL FIELD CAPACITY
      PPFC=(WCT*V*.36)*NB
C ACTUAL FIELD  CAPACITY
      PAFC=PPFC*PFE
C HOURS REQUIRED
      HOURS=AREA/PAFC
C DAYS REQUIRED
      NDAY=HOURS/PHOUR
      NC=NC+1
      IF(TEF.LT.0.60) GOTO 80
C MATCH TRACTOR & IMPLEMENT
      IF(ACPUL.GT.UDRFT*1.5) GOTO 80
   90 IF(ACPUL.LT.UDRFT*1.2) GOTO 80
      IF(WT.GT.POWER/2) GOTO 80
      CALL MAC
      WRITE(9,666)
  666 FORMAT(1H ,'FINISHED')
      IF(TY.LT.1.0)GOTO 80
  200 WRITE(11,904)
      WRITE(11,905)
      WRITE(11,906)
      WRITE(11,907)POWER,WT,MN,ACPUL,TPULL,TEF,TWD,TD,TH,DFLN,SLIP
      WRITE(11,920)
      WRITE(11,921)
      WRITE(11,922)
      WRITE(11,923)NB,WCT,DPC,LDA,PFE,PPFC,PAFC,UDRFT
      WRITE(11,940)
      WRITE(11,941)
      WRITE(11,942)
      WRITE(11,943)CI,BD,SPW1,M,FC,CRTN
```

APPENDIX H.1 (CONTINUED)

```
      WRITE(11,960)
      WRITE(11,961)
      WRITE(11,962)
      WRITE(11,963)HOURS,PRBTY,AREA,NDAY,V
      WRITE(11,970)IS,JS
   80 CONTINUE
   81 CONTINUE
      DPC=DPC-DDPC
   82 CONTINUE
      NB=NB-DNB
   83 CONTINUE
      V=V-DV
      V=V-TR
      IF(V.LT.MINV)V=MINV
   84 CONTINUE
      CALL MAST
      STOP
   50 FORMAT(6A4)
   51 FORMAT(3I2)
   53 FORMAT(I2)
   54 FORMAT(3F4.1)
   55 FORMAT(2F5.2)
  101 FORMAT(3I2,11F5.2)
  102 FORMAT(3F6.2,F5.1,I2,3I4,F5.2,I10,F5.2)
  103 FORMAT(3I2,F7.2)
  106 FORMAT(3F10.6)
  107 FORMAT(2I4)
  108 FORMAT(11F5.2)
  109 FORMAT(12I5)
  800 FORMAT(1H ' EXCESS PULL=',F10.6,' KN ')
  901 FORMAT(1H ' PULL EXCEEDED THE MAXIMUM')
  904 FORMAT(1H1 ,//,15X,'     6-  TRACTOR    SPECIFICATIONS')
  905 FORMAT(1H ,//,7X,'POWER','      WT ','       MN ','   ACPUL',
     1'   TPULL','      TEF','       TWD',
     1'      TD ','      TH ','      DFLN ','  SLIP')
  906 FORMAT(1H ,/,7X,'  KW      ','  KN      ','          '
     1,'   KN    ','   KN       ','  %       ','  M       ',
     1'  M       ','  M       ','  M       ',' %  ')
  907 FORMAT(7X,F6.2,10F8.2)
  920 FORMAT(1H ,////,15X,'    7-  PLOUGH SPECIFICATIONS')
  921 FORMAT(1H ,' ',//,'         NB','     WCT ','   DPC  ','    LOA '
     1,'   PFE  ','   PPFC ','   PAFC ','   UDRFT')
  922 FORMAT(1H ,8X,'     M   ','       M  ','   RAD.  ','        %  '
     1,'   HA/H ','   HA/H ','   KN   ')
  923 FORMAT(I8,7F8.2)
  940 FORMAT(1H ,////,15X,'     8-  SOIL      SPECIFICATIONS')
```

APPENDIX H.1 (CONTINUED)

```
941 FORMAT(1H ,/,6X,'   CI   ','    BD    ',' SPW1  ','  M    ',
   1'    FC    ','  CRTN  ')
942 FORMAT(1H ,6X,'  KP     ','   W/W  ','         ','     %  ','    MM '
   1,'        %FC  ')
943 FORMAT(6X,6F8.2)
960 FORMAT(1H ,///,15X,'      9- OPERATION')
961 FORMAT(1H ,/,8X,'HOURS   ',' PRBTY  ',' AREA  ',' NDAY   ','  V  ')
962 FORMAT(1H ,9X,'HOUR    ','  %     ','  HA    ',' DAY    ','M/SEC')
963 FORMAT(7X,F7.1,3I7,F7.2)
897 FORMAT(1H1,' ',/,20X,' FEASIBLE TRACTOR---IMPLEMENT
   1COMBINATIONS FOR  A ',I15,'     HECTARE FARM')
898 FORMAT(1H ,' ',//,10X,' STARTING WEEK NO. :',I10,
   1,'     DESIRABLE FINISHING WEEK NO. : ',I10)
899 FORMAT(1H ,' ',/,'    TRACTOR    SPECIFICATION      PLOUGH   SPECIFI
   1CATION   OPERATING   CONDITIONS            COST      OF        OPERATI
   1ON',/,'--------------------------  ------------------  -----------
   1--------------  ---------------------------------------------------')
990 FORMAT(1H ,' ',/,'REF LS POW WT  TEF TPUL ACPUL DRAFT NB DPC    V
   1 WRT  PB CRTN  M1    CI  FWK PWK PLPAC TRVAL PLVAL  KPAC  FUCOS LAC
   1OS PENAL TCOST')
991 FORMAT(1H ,'          KW  KN   %   KN   KN   KN       M   M/S  HA/H  %
   1   %FC  %   KP              POUND POUND POUND POUND POUND POUND PO
   1UND POUND')
970 FORMAT(2I4)
    END
```



APPENDIX H.2: FLOW CHART OF THE TRACTOR SELECTION PROGRAM

APENDIX H.3: SUBROUTINE ' MAC '

```
C            A SUBROUTINE FOR THE MACHINERY SELECTION
C
C                            PROGRAMME
C
C
      SUBROUTINE MAC
      WRITE(9,699)
  699 FORMAT(1H ,'MAC ENTERD')
      INTEGER*4 WTAB(10,54,10),PERIOD(10,10),XWK2,EXT,MINNB,LI
      INTEGER*4 WK1,WK2,NW,MI,KP,N,LN,AREA,MINWT,NB,ACOST,PWK
      INTEGER*4 TCASH,POWER,WT,DPLOW,TFCOST,TLCOST,ORVAL,PAC,CI
      INTEGER*4 NDAY,JS,IS,I,J,K,MAPRBT,MIPRBT,DPRBT,PRBTY,WKM,LF
     1,PLPAC
      REAL*4 CTAB(11),INCRTN,MACRTN,HOURS,MICRTN,MINV,MINTWD,M,TY
      REAL*4 FC,Y,YM,LOS,CASH,PRICE,A,B,C,PAFC,ACPUL,PFE
      DIMENSION MACH(6)
      COMMON/COMAC/ MACRTN,IS,JS,NDAY,CRTN,INCRTN,WK1,WK2,MICRTN,J
      COMMON/COMAN/ MINTWD,WKM,PRICE,A,B,C,TPULL,TEF,DPC,UDRFT,CI
      COMMON/CAMON/ MAPRBT,MIPRBT,DPRBT,PRBTY,MINNB,MINV,M
      COMMON/COMNES/ NB,HOURS,POWER,PAFC,WT,MINWT,AREA,TFCOST,
     1TLCOST,TCASH,ORVAL,PAC,TD,TH,MACH,IGROUP,ITYPE,IW,LIFE
     1,DNBCAP,DNICAP,DNFLAT,ALCH,UFCOST,DPLOW,LI,ACPUL,PLPAC,V
      COMMON/COM/ KGROUP,KTYPE,KIW,KORVAL,KPAC
      COMMON/COMN/ WTAB,CTAB,TY,IX,FC,LDA,WCT,SLIP,SPW1,PFE
      COMMON/COMS/ ACOST,K,PWK
      DPLOW=0
      KPAC=0
      PLPAC=0
      TY=0.0
      PWK=0
      LF=1
      ACOST=0
      TFCOST=0
      ORVAL=0
      TLCOST=0
      TCASH=0.0
      LS=1
      CRTN=CTAB(J)
      MI=WK2
      JX=J
   50 DO 62 J=1,JS
      DO 61 I=1,IS
      PERIOD(I,J)=0
   61 CONTINUE
   62 CONTINUE
      J=JX
      IF(WK2.LT.WK1)MI=WK2+52
      K=WK1
      DO 13 KK=WK1,MI
```

APPENDIX H.3 (CONTINUED)

```
      IF(K.GT.52)K=K-52
      DO 12 I=1,IS
      PERIOD(I,J)=PERIOD(I,J)+WTAB(I,K,J)
      PRBTY=((MAPRBT+DPRBT)-(I*DPRBT))
      IF(NDAY.LE.PERIOD(I,J)) GOTO 800
   12 CONTINUE
      K=K+1
   13 CONTINUE
      IF(J.GT.JS)WRITE(11,999)
      GOTO 798
  800 LI=LI+1
      WRITE(11,997)LI
      CALL COST
      TY=2.0
      PWK=K-WK2
      ACOST=TFCOST+TLCOST+TCASH+PLPAC+KPAC
      CALL STOR
      WRITE(12,998)LI,LS,POWER,WT,TEF,TPULL,ACPUL,UDRFT,NB,DPC,V,PAFC,
     1PRBTY,CRTN,M,CI,K,PWK,PLPAC,ORVAL,DPLOW,KPAC,
     1TFCOST,TLCOST,TCASH,ACOST
      N=WKM
      GOTO 350
  798 PK1=KK
      RM=NDAY/7
      IF(RM.GT.KK) WRITE(11,999)
      N=WKM
      IF(N.LT.WK1)N=N+52
      LS=2
      CRTN=CTAB(J)
      JX=J
    5 DO 47 J=1,JS
      DO 46 I=1,IS
      PERIOD(I,J)=0
   46 CONTINUE
   47 CONTINUE
      J=JX
      K=WK1
      DO 20 KK=WK1,N
      IF(K.GT.52)K=K-52
      DO 19 I=1,IS
      PERIOD(I,J)=PERIOD(I,J)+WTAB(I,K,J)
      PRBTY=((MAPRBT+DPRBT)-(I*DPRBT))
      IF(NDAY.LE.PERIOD(I,J)) GOTO 87
   19 CONTINUE
```

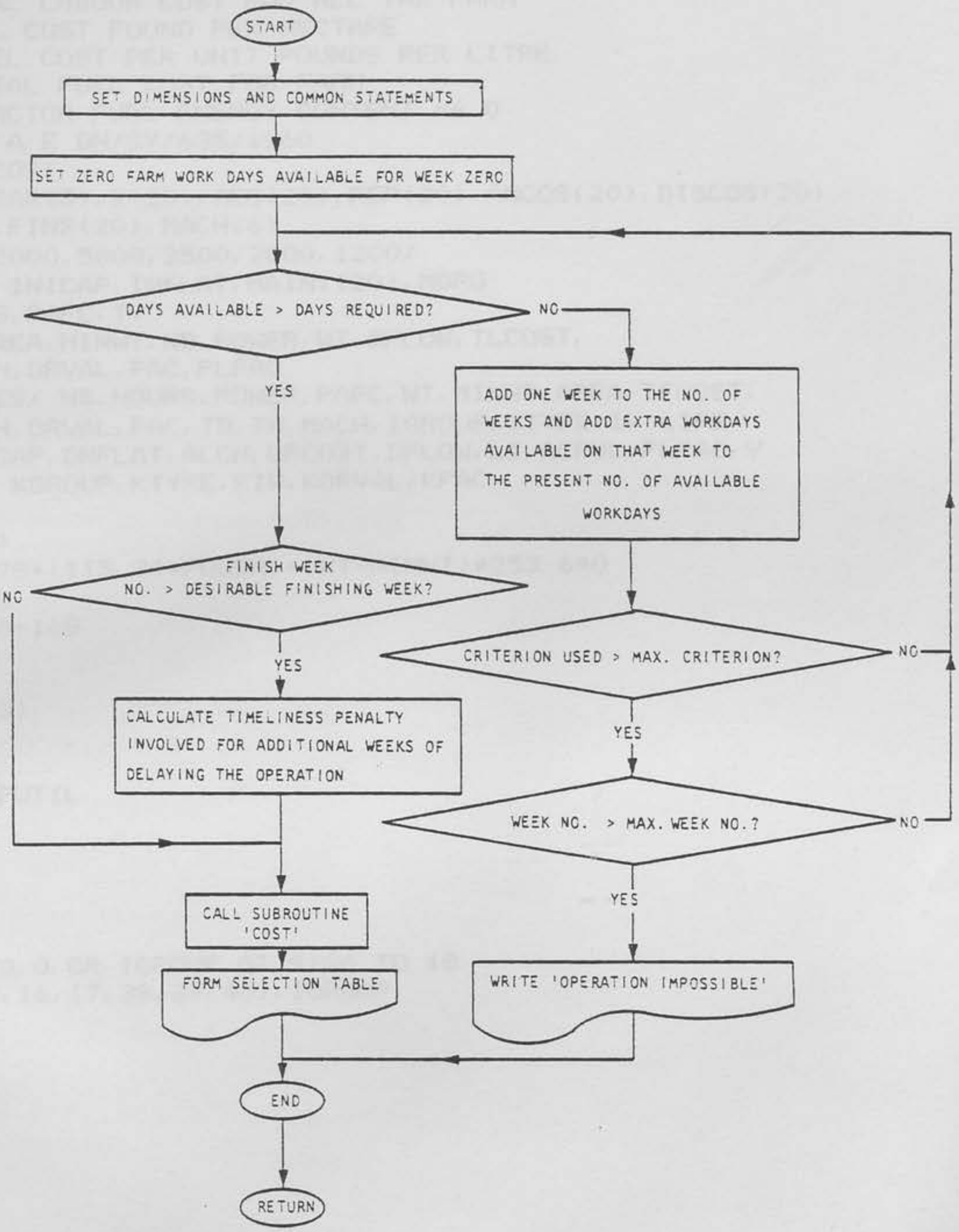
APPENDIX H.3 (CONTINUED)

```
      K=K+1
   20 CONTINUE
      CRTN=CRTN+INCRTN
      IF(J.GT.JS)WRITE(11,999)
      GOTO 797
   87 ACOST=0
      ORVAL=0
      TLCOST=0
      TFCOST=0
      TCASH=0
      LI=LI+1
      WRITE(11,997)LI
      CALL COST
      TY=2.0
      RM=NDAY/7
      IF(RM.GT.KK) WRITE(11,999)
      PK2=KK
      PWK=0
      PWK=PK2-PK1
      IF(WK2.LT.WK1)MI=WK2+52
      IF(K.LE.WK2) GOTO 350
      YM=(A*(MI)**2)+B*MI+C
      Y=((((A*K**2))+(B*K))+C)
      LOS=(YM-Y)/2
      CASH=LOS*PRICE
      TCASH=CASH*AREA
      ACOST=TFCOST+TLCOST+TCASH+PLPAC+KPAC
      CALL STOR
      WRITE(12,998)LI,LS,POWER,WT,TEF,TFULL,ACFUL,UDRFT,NB,DPC,V,
     1PAFC,PRBTY,CRTN,M,CI,K,PWK,PLPAC,ORVAL,DPLOW,KPAC,
     1TFCOST,TLCOST,TCASH,ACOST
      WRITE(11,973)K,YM,Y,LOS,CASH,TCASH
  350 DO 31 I=1,IS
      WRITE(11,102)I,PERIOD(I,J)
   31 CONTINUE
CX        WRITE(11,996)
  200 WRITE(11,900)NDAY,I,J,WK1,WK2,K,N,PWK
CX    90 STOP 7
  101 FORMAT(2I2)
  102 FORMAT(1H ,/,6X,' AVAILABLE DAYS AT PROBABILITY LEVEL : ',
     1I6,' IS ',I6)
  103 FORMAT(11F5.2)
  900 FORMAT(9I8)
  973 FORMAT(1H ,//,20X,' 5- TIMLINESS COSTS',//,7X,'PENALTY ',
```

APPENDIX H.3 (CONTINUED)

```
   1'WEEK NO. IS',42X,I5,/,7X,'MAXIMUM YIELD IS',39X,'T/HA  '
   1,F5.2,/,7X,'TOTAL YIELD IS',41X,'T/HA  'F5.2,/,
   17X,'YEILD LOSS DUE TO LATE SOWING IS',23X,'T/HA  ',F5.2,
   1/,6X,' UNIT CASH LOST IS ',37X,'$/HA',F7.2,/,
   17X,'TOTAL CASH LOSS OF THE SYSTEM IS',23X,'$',I10)
997 FORMAT(1H1,//,17X,'ADDITIONAL INFORMATION FOR COMBINATION  NO. : '
   1,I10)
998 FORMAT(1H ,' ',//,2I3,2I4,F5.2,3F5.1,I3,3F5.2,I4,F5.2,1X,F5.2,
   1I5,2I4,8I6)
999 FORMAT(1H ' OPERATION IMPOSSIBLE')
797 RETURN
    END
```

APPENDIX H.4: FLOW CHART OF THE SUBROUTINE 'MAC'



APPENDIX H.5: SUBROUTINE 'COST'

```
CTHIS PROGRAMME IS A NEW VERSION OF N I A E'S PROGRAMME . THE INPUT FROM STREAM
C      ALCH   =LABOUR COST POUNDS/HOUR
C      ALCOST =LABOUR COST POUNDS/HECTARE
C      TLCOST =TOTAL LABOUR COST FOR ALL THE FARM
C      FCOST  =FUEL COST POUND PER HECTARE
C      UFCOST = FUEL COST PER UNIT POUNDS PER LITRE
C      TFCOST = TOTAL FUEL COST FOR FARM
C      TFEC   = TRACTOR FUEL ENERGY CONTENT =6.0
C      SOURCE: N. I. A. E DN/SY/635/1960
      SUBROUTINE COST
      DIMENSION WEAR(5),X(20),AEC(20),REP(20),ANCOS(20),DISCOS(20)
     1,SINKEY(20),FINS(20),MACH(6)
      DATA WEAR/12000,5000,2500,2000,1200/
      REAL INBCAP,INICAP,INFLAT,MAINT(20),MORG
      REAL*4 HOURS,PAFC,TY
      INTEGER*4 AREA,MINWT,NB,POWER,WT,DPLOW,TLCOST,
     1TFCOST,TCASH,ORVAL,PAC,PLPAC
      COMMON/COMNES/ NB,HOURS,POWER,PAFC,WT,MINWT,AREA,TFCOST,
     1TLCOST,TCASH,ORVAL,PAC,TD,TH,MACH,IGROUP,ITYPE,IW,LIFE
     1,DNBCAP,DNICAP,DNFLAT,ALCH,UFCOST,DPLOW,LI,ACPUL,PLPAC,V
      COMMON/COM/ KGROUP,KTYPE,KIW,KORVAL,KPAC
      PL=0.0
      WRITE(9,111)
      KORVAL=361.78+(115.34*POWER)+(WT-MINWT)*253.6*0
      ORVAL=KORVAL
      DPLOW=397*NB-168
      FUTIL=800.0
      KLIFE=LIFE
      TWEAR=WEAR(3)
  700 TFEC=6.00
      SALVAL=0
      UTIL=HOURS+FUTIL
      IT=ITYPE
      IG=IGROUP
      TUTIL=0.0
      TMAINT=0.0
      N=LIFE
      IF(IGROUP.EQ.0.OR.IGROUP.GT.9)GO TO 18
      GO TO(14,15,16,17,38,39,40),IGROUP
   14 SF1=68
      SF2=0.92
      GO TO 18
```

APPENDIX H.5 (CONTINUED)

```
15 SF1=64
   SF2=0.885
   GO TO 18
16 SF1=60
   SF2=0.885
   GO TO 18
17 SF1=56
   SF2=0.885
   GO TO 18
38 SF1=79.9
   SF2=0.821
   GO TO 18
39 SF1=97.0
   SF2=0.796
   GO TO 18
40 SF1=78.2
   SF2=0.825
18 SALVAL=SF1*(SF2**N)
   IF(IGROUP.EQ.0.OR.IGROUP.GT.9)SALVAL=IGROUP
   V1=V*3.6
   VITA=6/V1
   IF(PL.EQ.1.0)WEAR(IW)=WEAR(IW)*VITA
    IF(PL.EQ.1.0)UTIL=HOURS
   DO 26 I=1,N
   FINS(I)=SF1*(SF2**I)
   TUTIL=TUTIL+UTIL
   X(I)=100*TUTIL/WEAR(IW)
   IF(X(I).LT.0)GO TO 26
   GO TO(19,20,21,22,23,24,25),ITYPE
19 MAINT(I)=0.1*X(I)**1.5
   GO TO 28
20 MAINT(I)=0.12*X(I)**1.5
   GO TO 28
21 MAINT(I)=0.096*X(I)**1.4
   GO TO 28
22 MAINT(I)=0.127*X(I)**1.4
   GO TO 28
23 MAINT(I)=0.159*X(I)**1.4
   GO TO 28
24 MAINT(I)=0.191*X(I)**1.4
   GO TO 28
25 MAINT(I)=0.301*X(I)**1.3
28 MAINT(I)=(MAINT(I)-TMAINT)/100
26 TMAINT=TMAINT+MAINT(I)*100
```

APPENDIX H.5 (CONTINUED)

```
      SALVAL=(SALVAL/100)*ORVAL
      IF(IGROUP.EQ.0.OR.IGROUP.GT.9)SALVAL=IGROUP
      IF(PL.EQ.1.0)GO TO 439
      WRITE(11,56)MACH
   56 FORMAT(1H ,/,7X,' PRESENT ANNUAL COST OF ',6A4/
     1,7X,'++++++++++++++++++++++++++')
  439 IF(PL.EQ.0.0)WRITE(11,703)
      IF(PL.EQ.1.0)WRITE(11,702)
  702 FORMAT(1H1,//,15X,'2-  THE  PLOUGH  ',/,'')
  703 FORMAT(1H ,//,15X'1- * THE  TRACTOR  ',/,' ')
  721 WRITE(11,29)IGROUP,ITYPE,IW
      WRITE(11,7)ORVAL,LIFE,SALVAL,UTIL,WEAR(IW),DNBCAP,DNICAP,DNFLAT
CX    IF(IGROUP.GT.ORVAL)GO TO 97
      INBCAP=DNBCAP/100.0
      INICAP=DNICAP/100.0
      INFLAT=DNFLAT/100.0
      DISTOT=0.0
   29 FORMAT(1H ,6X,'MACHINE TYPE',45X,3I3)
    7 FORMAT(1H ,6X,'PURCHASE PRICE OF MACHINE ',29X,'$',F8.1/
     1,6X,' CURRENT VALUE OF',I3,' YEAR OLD MACHNE ',19X,'$ ,',2X,F6.1/
     1,6X,' ANNUAL USAGE',43X,'H',F7.1,/
     1,6X,' WEAR OUT LIFE',42X,'H ',F7.1,//
     1,7X,'INTEREST RATE ON BORROWED CAPITAL  ',20X,'%',6X,F4.1,/
     1,6X,' INTEREST RATE ON INVESTED CAPITAL ',20X,'%',6X,F4.1,/
     2,6X,' INFLATION RATE  ',39X,'%',6X,F4.1,//)
C CALCULATE ANNUAL CASH FLOW
      G=1+INFLAT
      R=1+INICAP
      SINFUN=((ORVAL-SALVAL)*(G**N))/R**N
      ADD=0.0
      DO 2 NCOUNT=1,N
    2 ADD=ADD+(G/R)**NCOUNT
      SINFUN=SINFUN/ADD
      SALVAL=SALVAL/ORVAL
      FACTI=(1+INBCAP)**LIFE
      MORG=(ORVAL*INBCAP*FACTI)/(FACTI-1)
      VO=MORG*(R**N-1)/(R**N*INICAP)
      DO 8 IY=1,N
      Y=IY
      SINKEY(IY)=SINFUN*G**Y
      ORGY=ORVAL*(G**Y)
      RESALE =0.0
      REP(IY)=MAINT(IY)*ORGY
      IF(IY.NE.N)GO TO 6
      RESALE=(SALVAL*ORGY)
    6   ANCOS(IY)=MORG+REP(IY)-RESALE
      DISCOS(IY)=ANCOS(IY)/(R**Y)
    8 DISTOT=DISTOT+DISCOS(IY)
      F=N
      IF(R.NE.G)F=(G/R**N)*((R**N-G**N)/(R-G))
      DO 12 I=1,N
      AEC(I)=(DISTOT/F)*G**I
   12 CONTINUE
```

APPENDIX H.5 (CONTINUED)

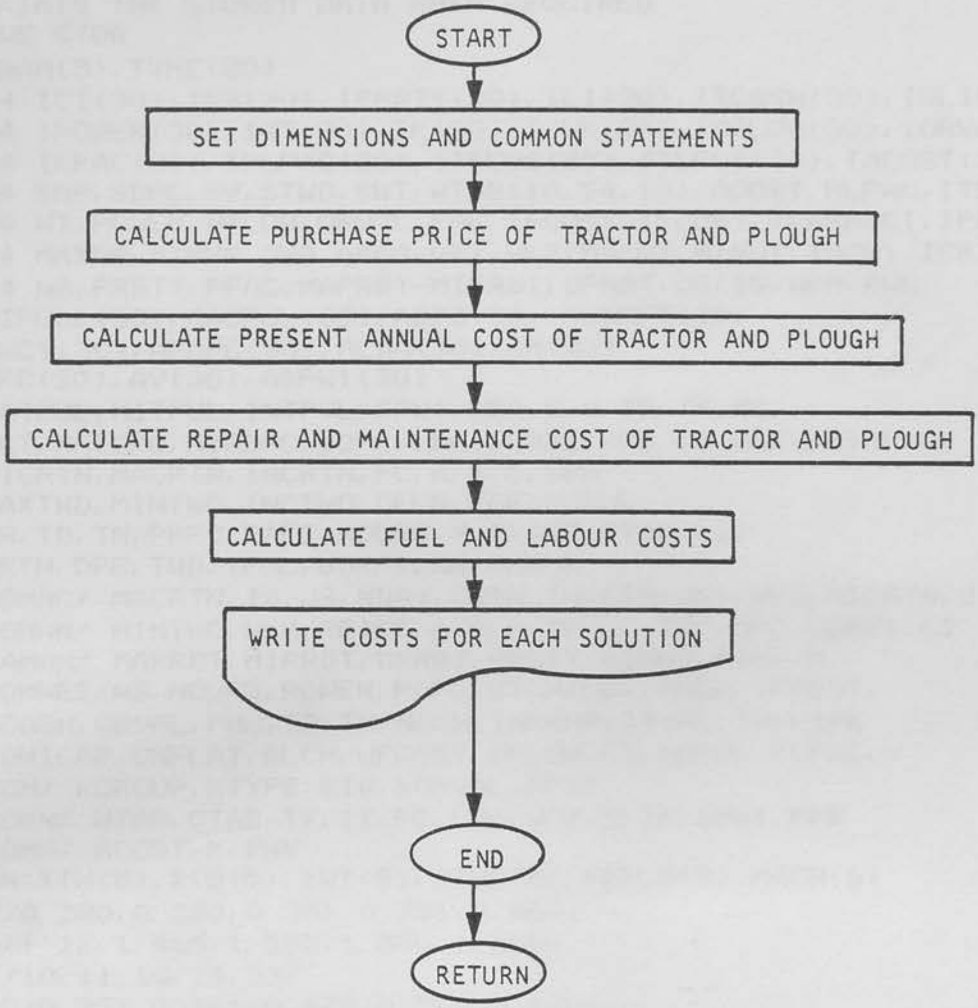
```
      PAC=DISTOT/F
      IF(PL.EQ.0.0)IPAC=PAC
      IF(PL.EQ.1.0)PLPAC=PAC
      KPAC=(IPAC*HOURS)/(HOURS+FUTIL)
      WRITE(9,707)PAC,PLPAC,PL
  707 FORMAT(2I8,F4.2)
  723 WRITE(11,10)MORG,LIFE,RESALE
      N1=N+1
      REPL=ORVAL*G**N-RESALE
      WRITE(11,32)N1,REPL
   32 FORMAT(1H ,6X,'COST OF REPLACING THE MACHINE AT THE '
     1'START OF YEAR ',I2,' $',3X,F7.1/)
   31 FORMAT(1H ,/,7X,' PRESENT ANNUAL COST OF MACHINE $',F7.1/
     1,7X,'****************************************'/)
   13 FORMAT(1H ,/,7X,'TOTAL PRESENT COST OF OWING MACHINE  $',F8.1)
      WRITE(11,11)
   11 FORMAT(1H ,17X,'REPAIRS    ANNUAL    DISCOUNTED'
     1' EQUIVALENT SINKING'/,29X,'CASH FLOW'
     2' CASH FLOW  ANNUAL      FUND'/,50X,
     5'COST        CASH FLOW'/,18X,
     4'$/YEAR      $/YEAR      $/YEAR      $/YEAR      $/YEAR'/)
   10 FORMAT(1H ,6X,'ANNUAL MORTGAGE REPAYMENTS ',28X,'$    ',F7.1,/
     1,7X,'SALVAGE VALUE OF MACHINE AFTER',I3,' YEARS',16X,'$    ',F7.1)
      WRITE(11,9)((IY,REP(IY),ANCOS(IY),DISCOS(IY),AEC(IY),SINKEY(IY))
     1,IY=1,N)
    9 FORMAT(1H ,7X,'YEAR',I3,F9.0,F11.0,F10.0,F11.0,F11.0)
      WRITE(11,13)DISTOT
      WRITE(11,31)PAC
CX   97 WRITE(11,98)
   98 FORMAT(1X/,'** STOP **'/
     1' RESALE VALUE GREATER THAN PURCHASE PRICE'/)
C
C   CALCULATE FUEL & LABOUR COSTS FOR PLOUGHING
      ALCOST=ALCH/PAFC
      TLCOST=ALCOST*AREA
      KOWER=POWER*0.8
      FCOST=(UFCOST*KOWER)/(TFEC*PAFC)
      TFCOST=FCOST*AREA
C   CALCULATE FEUL & LABOUR COSTS FOR OTHER OPERATIONS
      GUTIL=HOURS+FUTIL
      TYRCOS=GUTIL*0.15
      LCOS2=ALCH*FUTIL
      KLCOST=TLCOST+LCOS2
      JOWER=POWER*0.6
```

APPENDIX H.5 (CONTINUED)

```
      KFCOS=(JOWER*UFCOST)/TFEC
      KFCOS2=KFCOS*FUTIL
      KFCOST=TFCOST+KFCOS2
C     CALCULATE ANNUAL COST OF THE PLOW
      FAT=(1-EXP(-0.0046*HOURS*(V1/6)))
      ILIFE=(4000*(6/V1)*FAT)/HOURS
      WRITE(9,709)V,V1,ILIFE,WEAR(IW)
  709 FORMAT(2F10.2,I20,F10.0)
      IF(PL.GT.0.5)GOTO 900
      WRITE(11,701)KPAC
      ORVAL=DPLOW
      LIFE=ILIFE
      IGROUP=3
      ITYPE=7
      IW=3
      PL=1.0
      GO TO 700
  900 IGROUP=KGROUP
      WEAR(3)=TWEAR
      ITYPE=KTYPE
      IW=KIW
      ORVAL=KORVAL
      LIFE=KLIFE
      WRITE(11,100)ALCH,TLCOST,LCOS2,KLCOST,TFCOST,KFCOS2
     1,KFCOST,UFCOST
      IF(PL.EQ.1.0)GOTO 90
  701 FORMAT(1H ,///,7X,'  PRESENT ANNUAL COST OF THE TRACTOR FOR PLOUGH
     1ING ONLY  IS:  ',I15,'   POUNDS ')
  100 FORMAT(1H ,//,20X,' 3-  LABOUR COST',//,7X,'PRICE PER HOUR',
     141X,'$/H  ',F6.2,
     1,/,7X,'FOR PLOUHGING IS',39X,'$',I10,/,7X,'FOR OTHER OPERATIONS IS
     1',32X,'$',I10,
     1/,7X,'TOTAL LAROUR COST OF THE SYSTEM IS',21X,'$',I10,
     1//,20X,'4-   FUEL  COST',//,7X,'FOR PLOUGHING',42X,'$',I10,/,7X,
     1' FOR OTHER OPERATIONS',34X,'$',I10,/,7X,' FOR ALL THE SYSTEM ',
     135X,'$',I10,/,7X,' UNIT PRICE OF THE FEUL IS',29X,'$/L ',F7.2,)
  111 FORMAT(' COST ENTERED')
  112 FORMAT(' COST ENDED')
      WRITE(9,112)
C CALCULATE FUEL & LABOUR COSTS
   90 RETURN
      END
```

APPENDIX H.6: THE FLOW CHART OF SUBROUTINE 'COST'

SUBROUTINE 'COST'



APPENDIX H.7: SUBROUTINE 'STOR'

```
THIS SUBROUTINE STORES THE OUTPUT DATA IN A ONE DIMENTIONAL
ARRAY AND PRINTS THE STORED DATA WHEN REQUIRED
   SUBROUTINE STOR
   REAL*8 TNAM(5),TYRE(30)
   INTEGER*4 ICI(30),INB(30),IPRBTY(30),ILI(30),ITCASH(30),ISLIP(30)
   INTEGER*4 IPOWER(30),IWT(30),IK(30),IPWK(30),IDPLOW(30),1ORVAL(30)
   INTEGER*4 IKPAC(30),IPLPAC(30),ITFCOS(30),ITLCOS(30),IACOST(30)
   INTEGER*4 SNB,SDPC,SV,STWD,SWT,WTAB(10,54,10),ACOST,PLPAC,ITEF(30)
   INTEGER*4 WT,POWER,DPLOW,ORVAL,PAC,TFCOST,TLCOST,TCASH,CI,IPFE
   INTEGER*4 MAXNB,MINNB,DNB,AREA,WK1,WK2,MAXWT,MINWT,INCWT,ICRTN(30)
   INTEGER*4 NB,PRBTY,PFAC,MAPRBT,MIPRBT,DPRBT,JS,IS,WKM,PWK
   REAL*4 ATPULL(30),AACPUL(30),ADPC(30),AUDRFT(30)
   REAL*4 AWCT(30),APAFC(30),ALDA(30),AM(30)
   REAL*4 AFC(30),AV(30),ASPW1(30)
   REAL*4 MATPUL,MITPUL,INTPUL,SPW1,LDA,G,V,TR,TY,FC
   REAL*4 WCT,MAXDPC,MINDPC,DDPC,LDA1,LDA2,PFE,BD,MAXV,MINV,DV
   REAL*4 MICRTN,MACRTN,INCRTN,FC,A,B,C,SPW
   REAL*4 MAXTWD,MINTWD,INCTWD,DFLN,TEF,ACPUL
   REAL*4 TH,TD,TN,PPFC,PAFC,HOURS,M,PRICE,CTAB(11)
   REAL*4 CRTN,DPC,TWD,TPNL,UDRFT,MN,PHOUR
   COMMON/COMAC/ MACRTN,IS,JS,NDAY,CRTN,INCRTN,WK1,WK2,MICRTN,J
   COMMON/COMAN/ MINTWD,WKM,PRICE,A,B,C,TPULL,TEF,DPC,UDRFT,CI
   COMMON/CAMON/ MAPRBT,MIPRBT,DPRBT,PRBTY,MINNB,MINV,M
   COMMON/COMNES/NB,HOURS,POWER,PAFC,WT,MINWT,AREA,TFCOST,
  1TLCOST,TCASH,ORVAL,PAC,TD,TH,MACH,IGROUP,ITYPE,IW,LIFE
  1,DNBCAP,DNICAP,DNFLAT,ALCH,UFCOST,DPLOW,LI,ACPUL,PLPAC,V
   COMMON/COM/ KGROUP,KTYPE,KIW,KORVAL,KPAC
   COMMON/COMN/ WTAB,CTAB,TY,IX,FC,LDA,WCT,SLIP,SPW1,PFE
   COMMON/COMS/ ACOST,K,PWK
   DIMENSION XTH(5),XTD(5),XWT(5),XTWD(5),XDFLN(5),MACH(6)
   DATA XTH/0.280,0.280,0.356,0.381,0.457/
   DATA XTD/1.26,1.465,1.585,1.550,1.605/
   DATA XWT/10,11,18,24,32/
   DATA XTWD/0.351,0.361,0.472,0.516,0.638/
   DATA XDFLN/0.035,0.037,0.053,0.061,0.079/
   DATA TNAM/'12.4-28','12.4-36','16.9-34','18.4-34','18.4-38'/
   ILI(LI)=LI
   IPOWER(LI)=POWER
   IWT(LI)=WT
   ITEF(LI)=TEF*100
   ATPULL(LI)=TPULL
   AACPUL(LI)=ACPUL
   ISLIP(LI)=SLIP*100
   INB(LI)=NB
   ADPC(LI)=DPC
```

APPENDIX H.7 (CONTINUED)

```
      AWCT(LI)=WCT
      APAFC(LI)=PAFC
      ALDA(LI)=LDA
      ICRTN(LI)=CRTN*100+0.5
      AUDRFT(LI)=UDRFT
      AM(LI)=M
      ICI(LI)=CI
      IPRBTY(LI)=PRBTY
      AV(LI)=V
      ASPW1(LI)=SPW1
      AFC(LI)=FC
      IK(LI)=K
      IPWK(LI)=PWK
      IDPLOW(LI)=DPLOW
      IORVAL(LI)=ORVAL
      IKPAC(LI)=KPAC
      IPLPAC(LI)=PLPAC
      ITFCOS(LI)=TFCOST
      ITLCOS(LI)=TLCOST
      IACOST(LI)=ACOST
      TYRE(LI)=TNAM(IX)
      ITCASH(LI)=TCASH
      RETURN
      ENTRY MAST
      IPFE=PFE*100
      WRITE(13,500)AREA,WK1,WK2,IPFE
      WRITE(13,501)
      WRITE(13,503)(ILI(JF),JF=1,LI)
      WRITE(13,502)
      WRITE(13,504)(IPOWER(JF),JF=1,LI)
      WRITE(13,505)(IWT(JF),JF=1,LI)
      WRITE(13,506)(ITEF(JF),JF=1,LI)
      WRITE(13,507)(ATPULL(JF),JF=1,LI)
      WRITE(13,508)(AACPUL(JF),JF=1,LI)
      WRITE(13,509)(ISLIP(JF),JF=1,LI)
      WRITE(13,499)(TYRE(JF),JF=1,LI)
      WRITE(13,600)
      WRITE(13,599)(AUDRFT(JF),JF=1,LI)
      WRITE(13,601)(INB(JF),JF=1,LI)
      WRITE(13,602)(ADPC(JF),JF=1,LI)
      WRITE(13,603)(AWCT(JF),JF=1,LI)
      WRITE(13,604)(APAFC(JF),JF=1,LI)
      WRITE(13,605)(ALDA(JF),JF=1,LI)
      WRITE(13,606)
      WRITE(13,607)(ICRTN(JF),JF=1,LI)
      WRITE(13,608)(AM(JF),JF=1,LI)
      WRITE(13,609)(ICI(JF),JF=1,LI)
      WRITE(13,700)(ASPW1(JF),JF=1,LI)
      WRITE(13,701)(AFC(JF),JF=1,LI)
      WRITE(13,702)
```

APPENDIX H.7 (CONTINUED)

```
      WRITE(13,703)(IPRBTY(JF),JF=1,LI)
      WRITE(13,704)(AV(JF),JF=1,LI)
      WRITE(13,705)(IK(JF),JF=1,LI)
      WRITE(13,706)(IPWK(JF),JF=1,LI)
      WRITE(13,707)
      WRITE(13,708)(IDPLOW(JF),JF=1,LI)
      WRITE(13,709)(IORVAL(JF),JF=1,LI)
      WRITE(13,800)(IKPAC(JF),JF=1,LI)
      WRITE(13,801)(IPLPAC(JF),JF=1,LI)
      WRITE(13,802)(ITFCOS(JF),JF=1,LI)
      WRITE(13,803)(ITLCOS(JF),JF=1,LI)
      WRITE(13,804)(ITCASH(JF),JF=1,LI)
      WRITE(13,805)(IACOST(JF),JF=1,LI)
      WRITE(13,806)
500   FORMAT(1H1,//,30X,'SUMMARY TABLE',//,4X,'    FEASIBLE TRACTOR-IPLEM
     1ENT COMBINATIONS FOR A',I6,' HA FARM',/,6X,' OPERATION STARTING AT
     1 WEEK',I6,' AND EXPECTED TO FINISH AT WEEK',I8,/,'       PLOUGH OPER
     1ATING AT',I8,' % FIELD  EFFICIENCY')
501   FORMAT(1H ,/,35X,'UNIT',10X,' COMBINATION NUMBER')
502   FORMAT(1H ,/,5X,'TRACTOR SPECIFICATION')
503   FORMAT(1H ,42X,10I8)
504   FORMAT(1H ,7X,'POWER',24X,'KW',4X,10I8)
505   FORMAT(1H ,7X,'WEIGHT',23X,'KN',4X,10I8)
506   FORMAT(1H ,7X,'TRACTIVE EFFICIENCY',10X,'%',5X,10I8)
507   FORMAT(1H ,7X,'THEORETICAL PULL',13X,'KN',4X,10F8.1)
508   FORMAT(1H ,7X,'ACTUAL PULL',18X,'KN',4X,10F8.1)
509   FORMAT(1H ,7X,'SLIP',25X,'%',5X,10I8)
499   FORMAT(1H ,7X,'TYRE SIZE',30X,10A8)
600   FORMAT(1H ,/,5X,'PLOUGH SPECIFICATION')
 599  FORMAT(1H ,7X,'PLOUGH DRAUGHT',15X,'KN',4X,10F8.1)
601   FORMAT(1H ,7X,'NUMBER OF PLOUGH BODIES',12X,10I8)
602   FORMAT(1H ,7X,'DEPTH OF CUT',17X,'M',5X,10F8.2)
603   FORMAT(1H ,7X,'WIDTH OF CUT',17X,'M',5X,10F8.2)
604   FORMAT(1H ,7X,'WORK RATE',20X,'HA/H  ',10F8.2)
605   FORMAT(1H ,7X,'LATERAL DIRECTIONAL ANGLE',4X,'RAD.   ',10F8.2)
606   FORMAT(1H ,/,5X,'SOIL SPECIFICATION')
607   FORMAT(1H ,7X,'WORKABILITY CRITERION',8X,'% FC  ',10I8)
608   FORMAT(1H ,7X,'MOISTURE CONTENT',13X,'%W/W  ',10F8.2)
609   FORMAT(1H ,7X,'CONE INDEX',19X,'KPA   ',10I8)
700   FORMAT(1H ,7X,'SPECIFIC WEIGHT',14X,'KPA/CM',10F8.2)
701   FORMAT(1H ,7X,'FIELD CAPACITY',15X,'MM',4X,10F8.2)
702   FORMAT(1H ,/,5X,'OPERATING CONDITIONS')
703   FORMAT(1H ,7X,'PROBABILITY LEVEL',12X,'%',5X,10I8)
704   FORMAT(1H ,7X,'TRAVEL SPEED',17X,'M/S',3X,10F8.2)
705   FORMAT(1H ,7X,'FINISHING WEEK NUMBER',14X,10I8)
706   FORMAT(1H ,7X,'NUMBER OF PENALTY WEEKS',12X,10I8)
707   FORMAT(1H ,/,5X,'COST OF OPERATION',3X,'POUNDS STERLING')
708   FORMAT(1H ,7X,'PLOUGH PURCHASE PRICE',14X,10I8)
709   FORMAT(1H ,7X,'TRACTOR PURCHASE PRICE',13X,10I8)
800   FORMAT(1H ,7X,'PRESENT ANNUAL COST OF TRACTOR',5X,10I8)
```

APPENDIX H.7 (CONTINUED)

```
801   FORMAT(1H ,7X,'PRESENT ANNUAL COST OF PLOUGH',6X,10I8)
802   FORMAT(1H ,7X,'FUEL COST',26X,10I8)
803   FORMAT(1H ,7X,'LABOUR COST',24X,10I8)
804   FORMAT(1H ,7X,'TIMELINESS PENALTY',17X,10I8)
805   FORMAT(1H ,7X,'TOTAL COST OF THE SYSTEM',11X,10I8)
806   FORMAT(1H1,' ',6X)
 90   RETURN
      END
```

APPENDIX H.8: INPUT FILE- ENGINEERIG & OPERATIONAL DATA

THIS IS AN INPUT FILE FOR THE TRACTOR SELECTION PROGRAM WHICH IS READ THROUGH CHANNEL 10 AND CONTAINS:

ON FIRST LINE MAXIMUM; MINIMUM AND DECREMENTS ON THE NUMBER OF PLOUGH BODIES AND DEPTH OF CUT, LATERAL DIRECTIONAL ANGLES, PLOUGH FIELD EFFICIENCY, SOIL BULK DENSITY, AND MAXIMUM; MINIMUM AND DECREMENS ON PLOUGHING SPEED;

ON SECOND LINE, MINIMUM; MAXIMUM AND INCRENENTS ON SOIL WORKABILITY CRITERION, FIELD CAPACITY, PERCENTAGE FACTOR WHICH IS A 2 DIGIT POSITIVE OR NEGATIVE NUMBER IF FIELD CAPACITY IS READ IN TERMS OF MM OR % OF WATER IN THE SOIL PROFILE, MAXIMUM; MINIMUM AND DECREMENT ON THE PROBABILITY LEVEL SOIL SPECIFIC WEIGHT, AREA AND POTENTIAL WORKING HOURS IN A DAY;

ON THIRD LINE STARTING, DESIRABLE FINISHING AND MAXIMUM DELAY WEEK NUMBER AND PRICE OF THE PRODUCT;

ON FORTH LINE ,COEFFICIENTS OF THE YIELD FUNCTION.

EXAMPLE

```
 5 2 100.4000.2000.10 0.85 0.50 0.80 1.28 3.00 0.50 0.50
  0.90  1.20  0.05110.020 100  80  10 0.00        30008.00
394250 100.00
 -0.035970  3.029779-58.199140
```

APPENDIX H.9:

THIS FILE IS AN INPUT FILFE FOR THE TRACTOR SELECTION
PROGRAM AND CONTAINS:
ON FIRST LINE THE SOIL WORKABILITY CRITERION AS PERCENT
OF FIELD CAPACITY OF THE SOIL;
ON SUBSEQUENT PAIRS OF LINES THE NUMBER OF AVAILABLE
DAYS FOR SOIL WORK AT 90 AND 100 PERCENT CRITERIA,RESPECTIVELY
FOR WEEKS 1 TO 52.

```
0.90 0.95 1.00 1.05 1.10
   0    0    0    5    7
   0    0    0    7    7
   0    0    0    0    7
   0    0    0    2    7
   0    0    0    0    7
   0    0    0    4    7
   0    0    0    0    7
   0    0    0    1    7
   0    0    0    2    7
   0    0    0    4    7
   0    0    0    2    7
   0    0    0    4    7
   0    0    0    2    7
   0    0    0    3    7
   0    0    0    7    7
   0    0    0    7    7
   0    0    0    7    7
   0    0    0    7    7
   0    0    0    7    7
   0    0    0    7    7
   0    0    0    6    7
   0    0    0    7    7
   0    0    0    7    7
   0    0    0    7    7
   0    0    0    6    7
   0    0    0    6    7
   0    0    0    5    7
   0    0    0    6    7
   0    0    0    5    7
   0    0    0    6    7
   0    0    0    6    7
   0    0    0    7    7
   0    0    0    7    7
   0    0    0    6    7
   0    0    0    6    7
   0    0    0    3    7
   0    0    0    5    7
   0    0    0    2    7
   0    0    0    5    7
   0    0    0    4    7
   0    0    0    7    7
   0    0    0    7    7
   0    0    0    7    7
   0    0    0    6    7
   0    0    0    7    7
```

APPENDIX H.9 (CONTINUED)

0	0	0	6	7
0	0	0	7	7
0	0	0	5	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	6	7
0	0	0	7	7
0	0	0	4	7
0	0	0	6	7
0	0	0	6	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	1	7	7
0	0	1	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	6	7
0	0	0	7	7
0	0	0	3	7
0	0	0	5	7
0	0	0	2	7
0	0	0	5	7
0	0	0	5	7
0	0	0	6	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	5	7
0	0	0	6	7
0	0	0	6	7
0	0	0	6	7
0	0	0	3	7
0	0	0	3	7
0	0	0	2	7
0	0	0	2	7
0	0	0	6	7
0	0	0	7	7
0	0	0	6	7
0	0	0	6	7
0	0	0	6	7
0	0	1	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7
0	0	0	7	7

APPENDIX H.10: DATA FOR COSTING ROUTINE

THESE DATA ARE READ THROUGH CHANNEL 5
FIRST LINE IS THE CAPTION 24 COLUMNS
SECOND LINE IS, MACHINE RESALE, REPAIR AND WEAR GROUP 2
COLUMNS EACH(INTEGER)
THIRD LINE IS, MACHINE LIFE 2 COLUMNS(INTEGER)
FORTH LINE IS, INFLATION AND INTEREST RATES
ON IN INVESTED AND BORROWED CAPITAL 4 COLUMNS EACH WITH ONE
DIGIT AFTER DECIMAL POINT
SIXTH LINE IS THE UNIT PRICES OF LABOUR& FUEL 5 COLUMNS EACH 2
DIGITS AFTER DECIMAL POINT

EXAMPLE

```
THE  TILLAGE SYSTEM
 1 2 1
 5
15.013.015.0
02.5000.13
```

FEASIBLE TRACTOR-IPLEMENT COMBINATIONS FOR A 300 HA FARM
OPERATION STARTING AT WEEK 39 AND EXPECTED TO FINISH AT WEEK 42
PLOUGH OPERATING AT 79 % FIELD EFFICIENCY

	UNIT	COMBINATION NUMBER 1	2	3	4	5
TRACTOR SPECIFICATION						
POWER	KW	91	91	64	64	48
WEIGHT	KN	32	32	32	32	24
TRACTIVE EFFICIENCY	%	72	71	72	71	72
THEORETICAL PULL	KN	34.4	34.4	34.4	34.4	25.8
ACTUAL PULL	KN	24.8	24.8	24.8	24.8	18.6
SLIP	%	10	11	10	11	11
TYRE SIZE		18.4-38	18.4-38	18.4-38	18.4-38	18.4-34
PLOUGH SPECIFICATION						
PLOUGH DRAUGHT	KN	17.7	17.1	20.2	19.5	14.6
NUMBER OF PLOUGH BODIES		3	3	4	4	3
DEPTH OF CUT	M	0.30	0.30	0.30	0.30	0.30
WIDTH OF CUT	M	0.33	0.33	0.33	0.33	0.33
WORK RATE	HA/H	0.75	0.75	0.70	0.70	0.53
LATERAL DIRECTIONAL ANGLE	RAD.	0.62	0.62	0.62	0.62	0.62
SOIL SPECIFICATION						
WORKABILITY CRITERION	% FC	105	110	105	110	110
MOISTURE CONTENT	%W/W	30.08	31.51	30.08	31.51	31.51
CONE INDEX	KPA	858	820	858	820	820
SPECIFIC WEIGHT	KPA/CM	13.05	13.05	13.05	13.05	13.05
FIELD CAPACITY	MM	110.00	110.00	110.00	110.00	110.00
OPERATING CONDITIONS						
PROBABILITY LEVEL	%	90	100	90	100	100
TRAVEL SPEED	M/S	2.64	2.64	1.85	1.85	1.85
FINISHING WEEK NUMBER		48	45	48	46	49
NUMBER OF PENALTY WEEKS		6	3	6	4	7
COST OF OPERATION POUNDS STERLING						
PLOUGH PURCHASE PRICE		1023	1023	1420	1420	1023
TRACTOR PURCHASE PRICE		10857	10857	7743	7743	5898
PRESENT ANNUAL COST OF TRACTOR		691	691	524	524	516
PRESENT ANNUAL COST OF PLOUGH		468	468	499	499	468
FUEL COST		621	621	472	472	468
LABOUR COST		996	996	1067	1067	1423
TIMELINESS PENALTY		18676	4482	18676	8134	25566
TOTAL COST OF THE SYSTEM		21452	7258	21238	10696	28441

APPENDIX H.12: ADDITIONAL INFORMATION FOR COMBINATION NO. :1

PRESENT ANNUAL COST OF THE TILLAGE SYSTEM

1- THE TRACTOR

MACHINE TYPE		1 2 1
PURCHASE PRICE OF MACHINE	£	10857.0
CURRENT VALUE OF 5 YEAR OLD MACHNE	£	4865.8
ANNUAL USAGE	H	1198.6
WEAR OUT LIFE	H	12000.0
INTEREST RATE ON BORROWED CAPITAL	%	15.0
INTEREST RATE ON INVESTED CAPITAL	%	13.0
INFLATION RATE	%	15.0
ANNUAL MORTGAGE REPAYMENTS	£	3238.8
SALVAGE VALUE OF MACHINE AFTER 5 YEARS	£	9786.9
COST OF REPLACING THE MACHINE AT THE 'START OF YEAR 6	£	12050.3

	REPAIRS £/YEAR	ANNUAL CASH FLOW' £/YEAR	DISCOUNTED' CASH FLOW £/YEAR	EQUIVALENT ANNUAL COST £/YEAR	SINKING FUND CASH FLOW £/YEAR
YEAR 1	473.	3712.	3285.	2393.	1427.
YEAR 2	994.	4233.	3315.	2751.	1641.
YEAR 3	1481.	4720.	3271.	3164.	1887.
YEAR 4	2017.	5256.	3223.	3639.	2170.
YEAR 5	2631.	-3917.	-2126.	4185.	2495.

TOTAL PRESENT COST OF OWING MACHINE £ 10968.2

PRESENT ANNUAL COST OF MACHINE £ 2080.0
****

PRESENT ANNUAL COST OF THE TRACTOR FOR PLOUGHING ONLY IS: £ 691

APPENDIX H.12: (CONTINUED)

2- THE PLOUGH

MACHINE TYPE		3 7 3
PURCHASE PRICE OF MACHINE	£	1023.0
CURRENT VALUE OF 5 YEAR OLD MACHNE	£	333.2
ANNUAL USAGE	H	398.6
WEAR OUT LIFE	H	1578.3
INTEREST RATE ON BORROWED CAPITAL	%	15.0
INTEREST RATE ON INVESTED CAPITAL	%	13.0
INFLATION RATE	%	15.0
ANNUAL MORTGAGE REPAYMENTS	£	305.2
SALVAGE VALUE OF MACHINE AFTER 5 YEARS	£	670.2
COST OF REPLACING THE MACHINE AT THE 'START OF YEAR 6	£	1387.4

	REPAIRS	ANNUAL CASH FLOW'	DISCOUNTED' CASH FLOW	EQUIVALENT ANNUAL COST	SINKING FUND CASH FLOW
	£/YEAR	£/YEAR	£/YEAR	£/YEAR	£/YEAR
YEAR 1	236.	541.	479.	539.	164.
YEAR 2	396.	701.	549.	619.	189.
YEAR 3	532.	838.	580.	712.	217.
YEAR 4	678.	983.	603.	819.	250.
YEAR 5	841.	476.	258.	942.	287.

TOTAL PRESENT COST OF OWING MACHINE £ 2469.3

PRESENT ANNUAL COST OF MACHINE £ 468.0
****

3- LABOUR COST

PRICE PER HOUR	£/H	2.50
FOR PLOUHGING IS	£	996
FOR OTHER OPERATIONS IS	£	2000
TOTAL LAROUR COST OF THE SYSTEM IS	£	2996

4- FUEL COST

FOR PLOUGHING	£	621
FOR OTHER OPERATIONS	£	800
FOR ALL THE SYSTEM	£	1421
UNIT PRICE OF THE FEUL IS	£/L	0.13

5- TIMLINESS COSTS

PENALTY WEEK NO. IS		43
MAXIMUM YIELD IS	T/HA	5.60
TOTAL YIELD IS	T/HA	5.57
YEILD LOSS DUE TO LATE SOWING IS	T/HA	0.01
UNIT CASH LOST IS	£/HA	1.38
TOTAL CASH LOSS OF THE SYSTEM IS	£	414

AVAILABLE DAYS AT PROBABILITY LEVEL : 1 IS 44

AVAILABLE DAYS AT PROBABILITY LEVEL : 2 IS 51

APPENDIX H.12: (CONTINUED)

6- TRACTOR SPECIFICATIONS

POWER	WT	MN	ACPUL	TPULL	TEF	TWD	TD	TH
KW	KN		KN	KN	%	M	M	M
91.00	32.00	9.52	24.83	34.38	0.72	0.64	1.60	0.46

7- PLOUGH SPECIFICATIONS

NB	WCT	DPC	LDA	PFE	PPFC	PAFC	UDRFT
	M	M	RAD.	%	HA/H	HA/H	KN
3	0.33	0.30	0.62	0.80	0.94	0.75	17.69

8- SOIL SPECIFICATIONS

CI	BD	SPW1	M	FC	CRTN
KP	W/W		%	MM	%FC
858.00	1.28	13.05	30.08	110.00	1.05

9- OPERATION

HOURS	PRBTY	AREA	NDAY	V
HOUR	%	HA	DAY	M/SEC
398.6	90	300	49	2.64